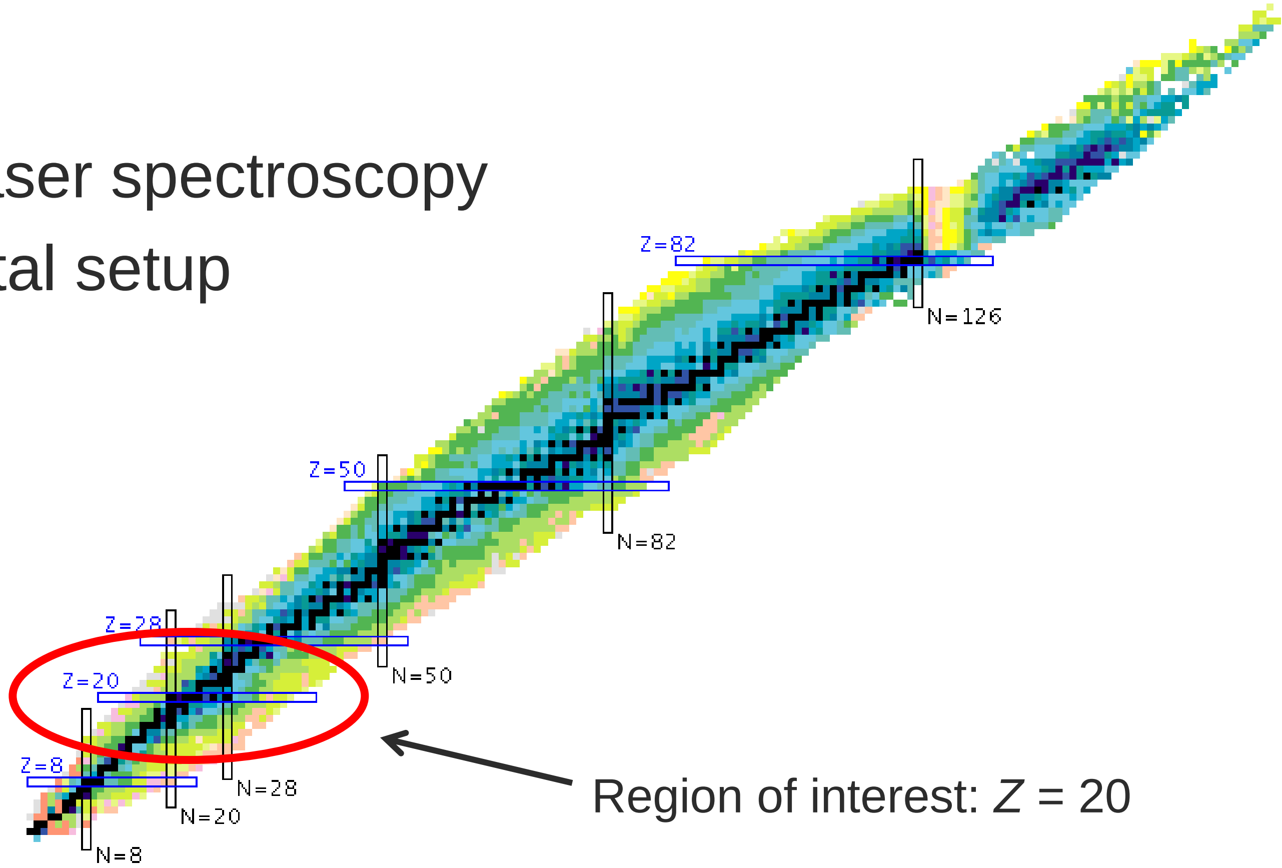
Laser Spectroscopy of neutron-rich K isotopes

BRIX Fall Day
2/12/2013

Jasna Papuga

Outline:

- Motivation
- Collinear laser spectroscopy
- Experimental setup
- Results
- Conclusion



Region of interest: Z = 20

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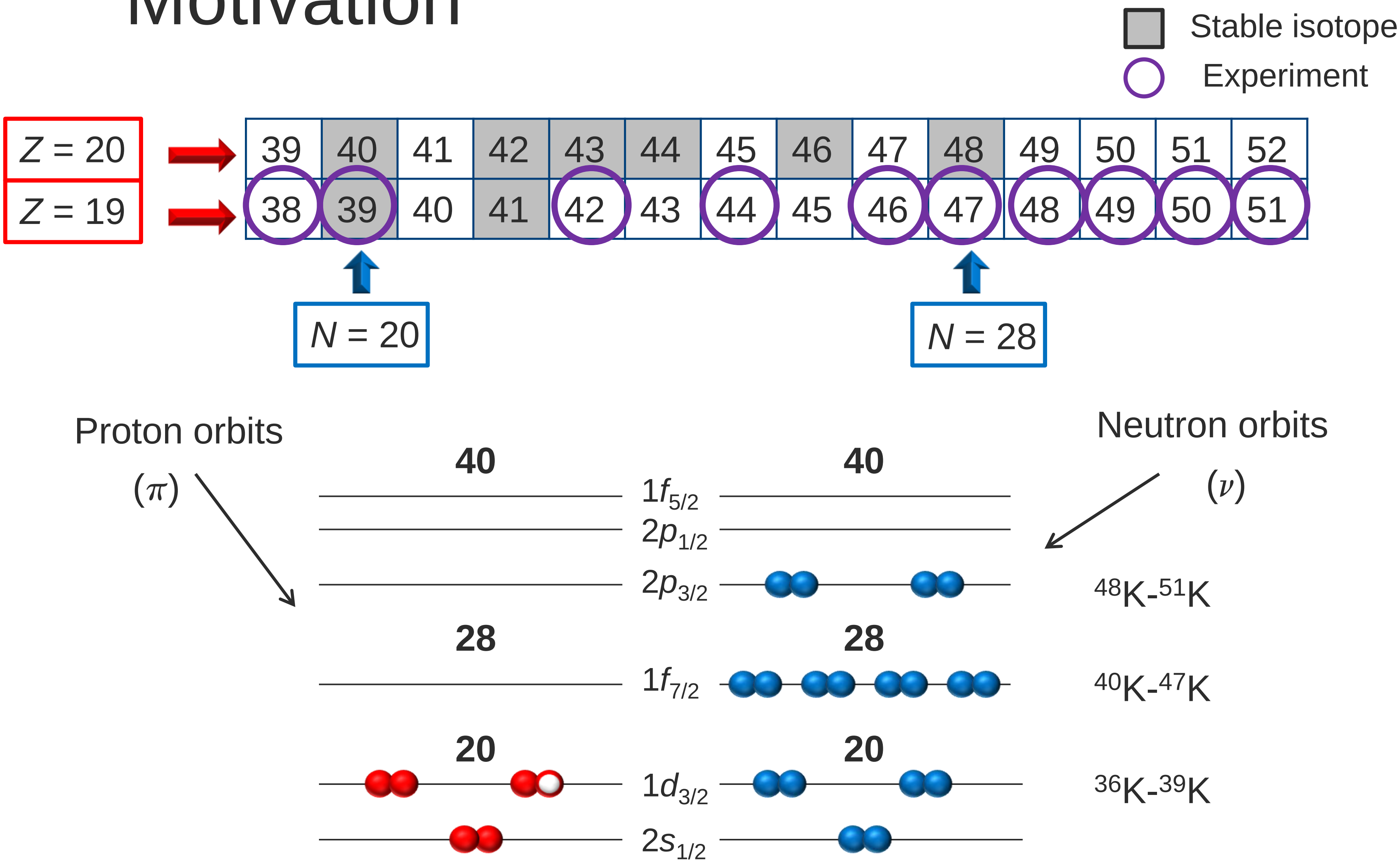
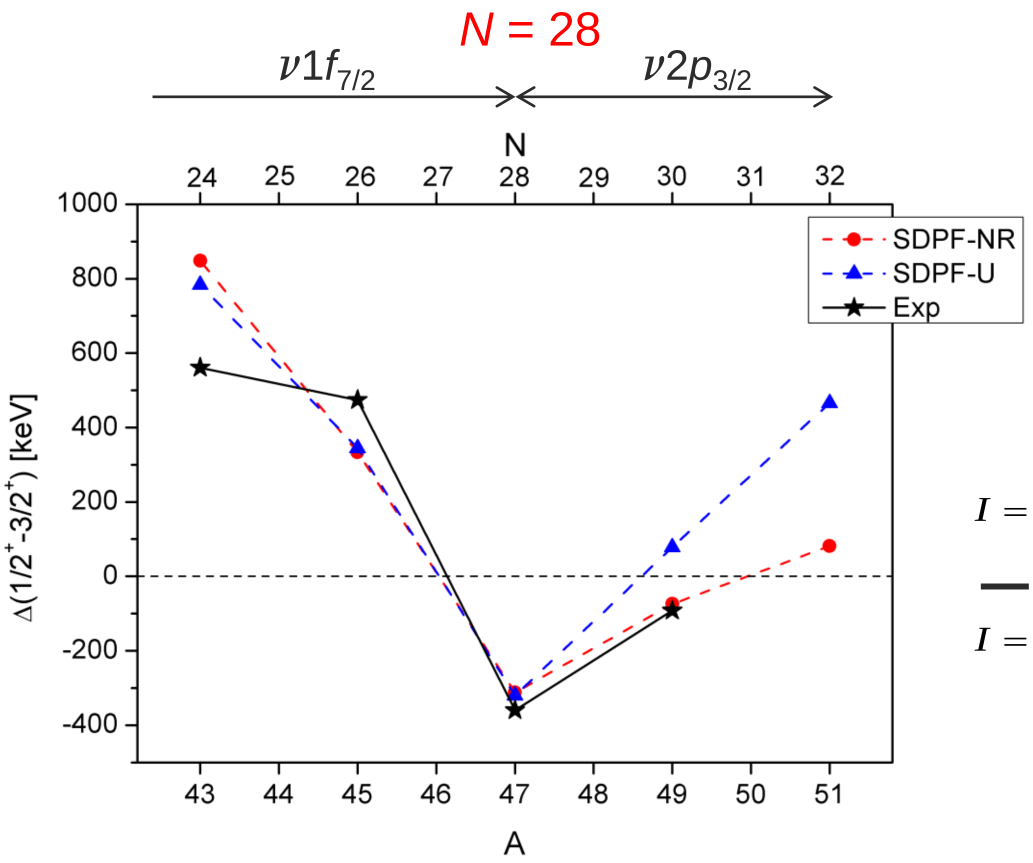
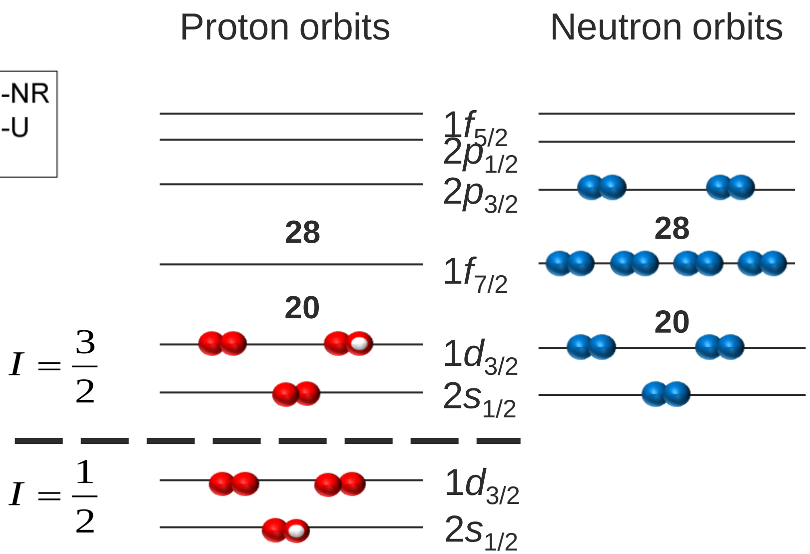
Motivation



Stable isotope
Experiment
Z = 20
Z = 19
39 40 41 42 43 44 45 46 47 48 49 50 51 52
38 39 40 41 42 43 44 45 46 47 48 49 50 51
N = 20
N = 28
Proton orbits
(π)
Neutron orbits
(ν)
40
28
20
1f5/2
2p1/2
2p3/2
1f7/2
1d3/2
2s1/2
48K-51K
40K-47K
36K-39K

Motivation: Evolution of $3/2^+$ and $1/2^+$ states





SDPF-NR: J. Retamosa *et al*., Phys. Rev. C 55, 1266 (1997)
S. Nummela *et al*., Phys. Rev. C 64, 054313 (2001)

SDPF-U: F. Nowacki and A. Poves, Phys. Rev. C 79, 014310 (2009)

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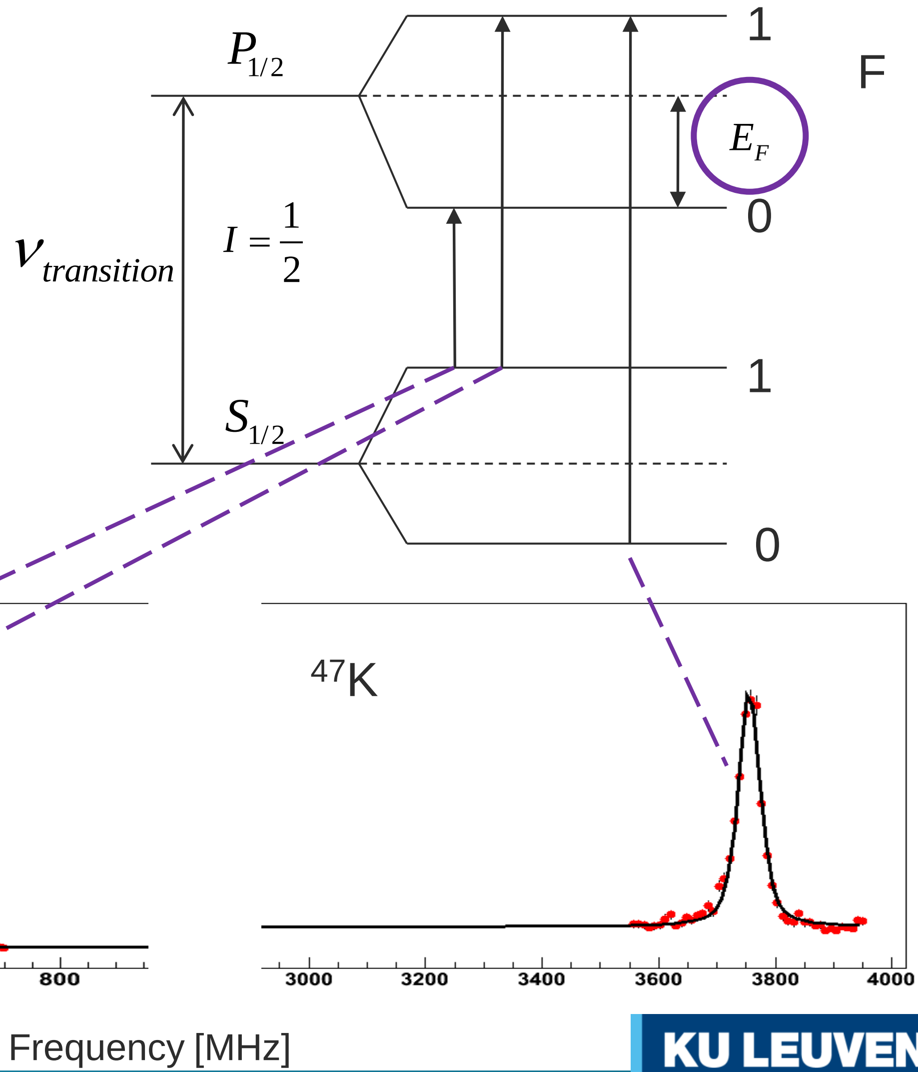
Collinear Laser Spectroscopy – measuring hyperfine splitting

- Hyperfine interaction couples the electron angular momentum (*J*) and nuclear spin (*I*)

- The total angular momentum:

$$\vec{F} = \vec{I} + \vec{J}$$



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Collinear Laser Spectroscopy – measuring hyperfine splitting

- Energy difference: $E_F = \frac{1}{2}AC + B\frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(I+1)J(J+1)}$ where $C = F(F+1) - I(I+1) - J(J+1)$

- Magnetic dipole HF parameter:

$$A = \frac{\mu_I B_J}{IJ}$$

- Electric quadrupole HF parameter:

$$B = eQV_{zz}$$

- Magnetic and quadrupole moment are deduced by relative measurement:

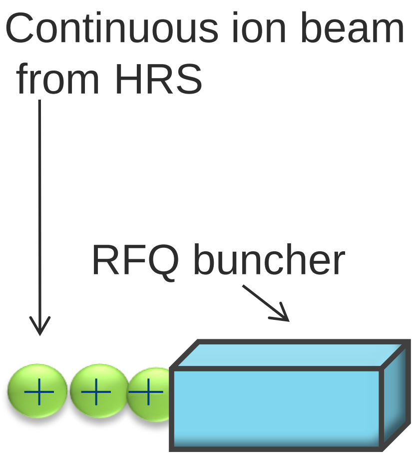
$$\mu = \frac{AI}{A_{ref} I_{ref}} \mu_{ref}$$

$$Q = \frac{B}{B_{ref}} Q_{ref}$$

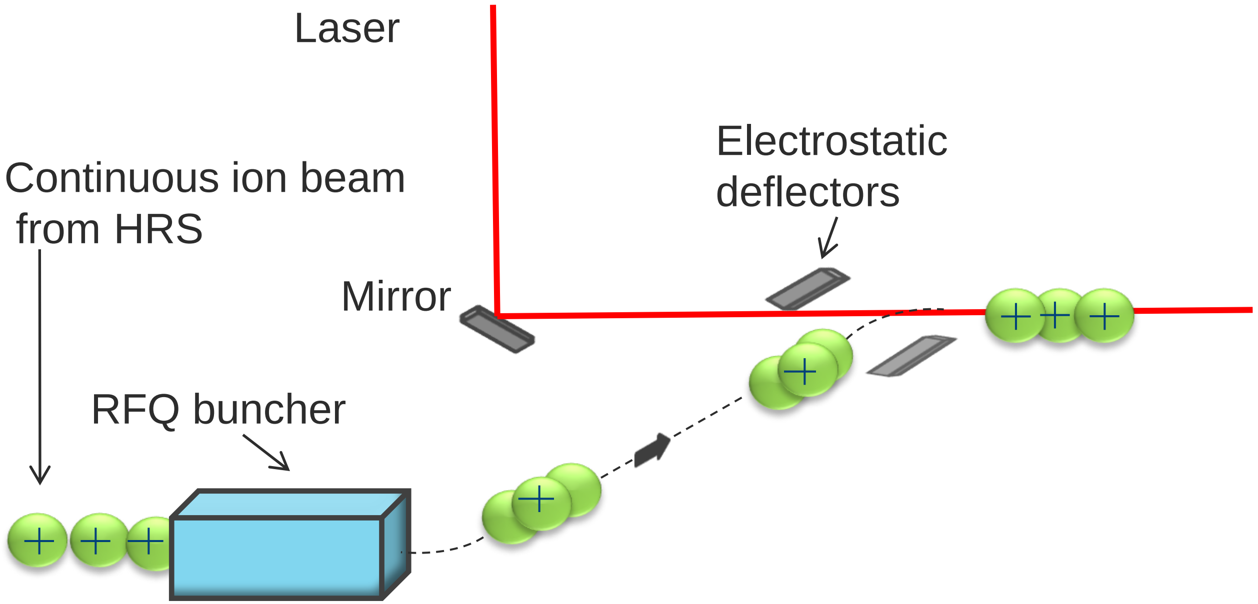
- Mean square charge radii :

$$\delta\nu = \nu^A - \nu^{ref} = K\frac{m_A - m_{ref}}{m_A \cdot m_{ref}} + F\delta\langle r^2 \rangle$$

Setup – Collinear Laser Spectroscopy



Setup – Collinear Laser Spectroscopy



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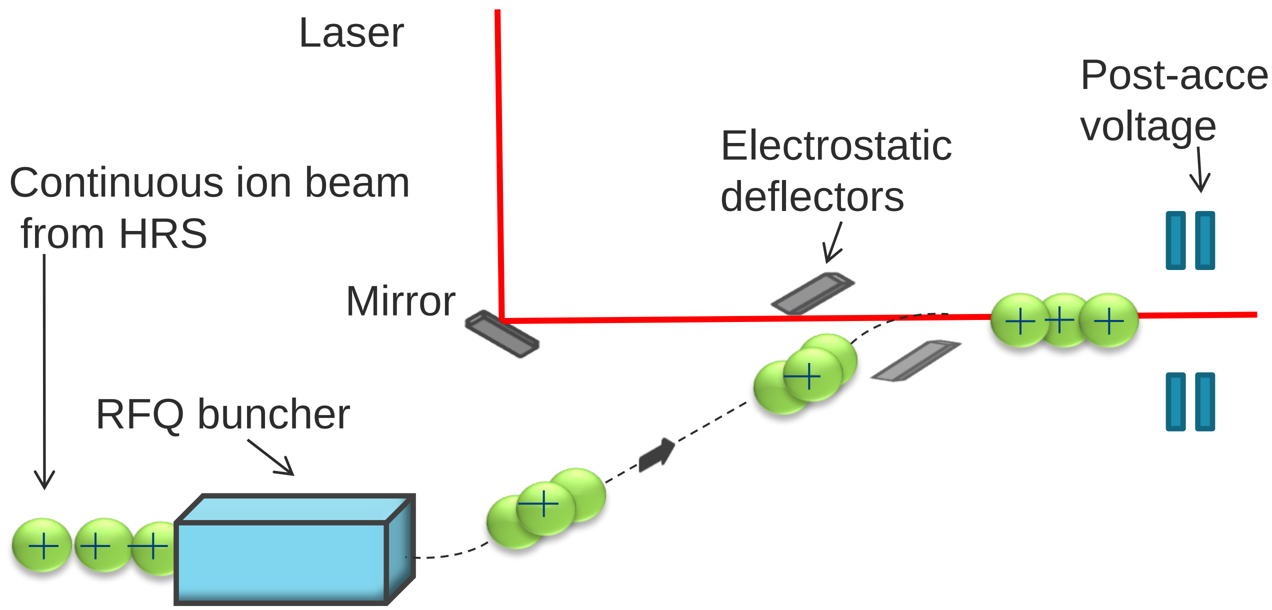
Setup – Collinear Laser Spectroscopy



Doppler tuning:

$$\nu_{transition} = \nu_{laser} \frac{1-\beta}{\sqrt{1-\beta^2}}$$

$$\beta = \sqrt{1 - \frac{M_0^2 c^4}{(Uq + M_0 c^2)^2}}$$

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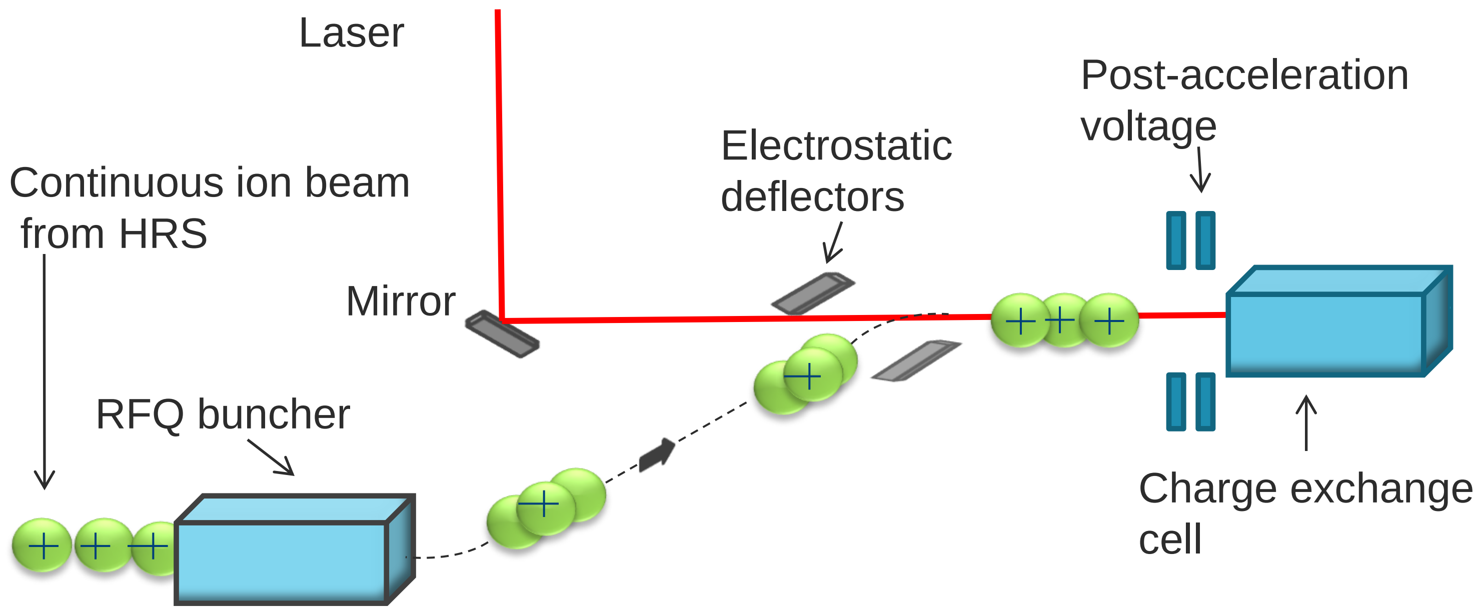
Setup – Collinear Laser Spectroscopy



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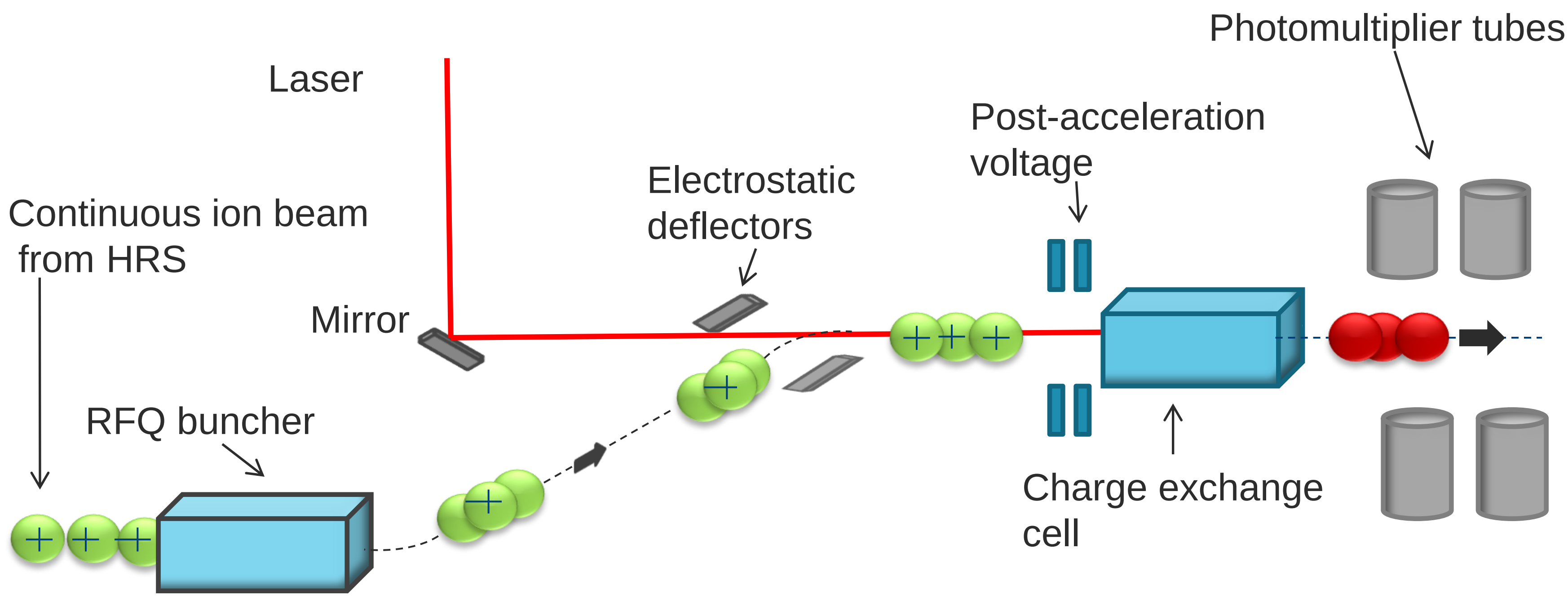
Setup – Collinear Laser Spectroscopy



Doppler tuning:

$$\nu_{transition} = \nu_{laser} \frac{1-\beta}{\sqrt{1-\beta^2}}$$

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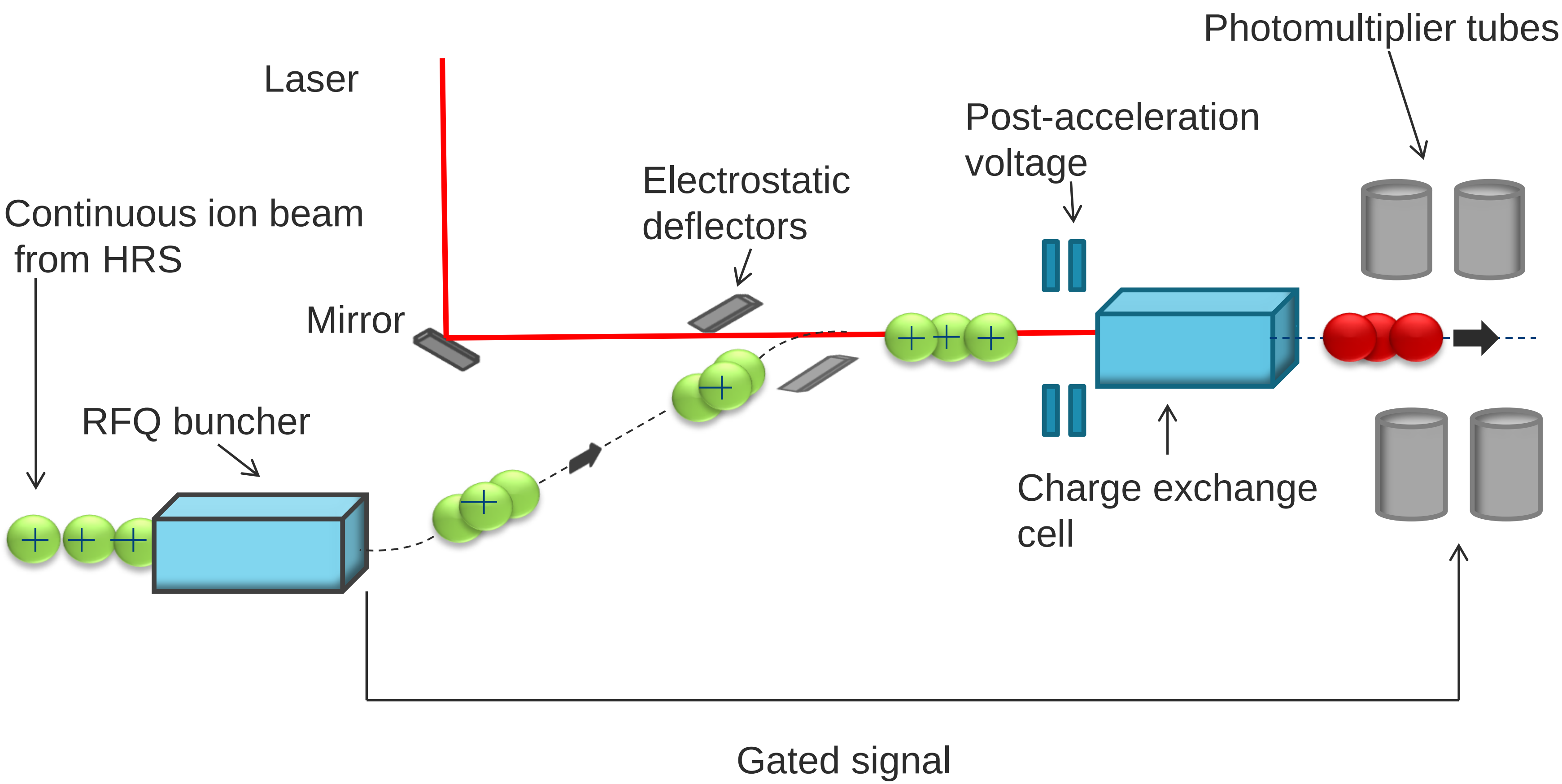
Setup – Collinear Laser Spectroscopy



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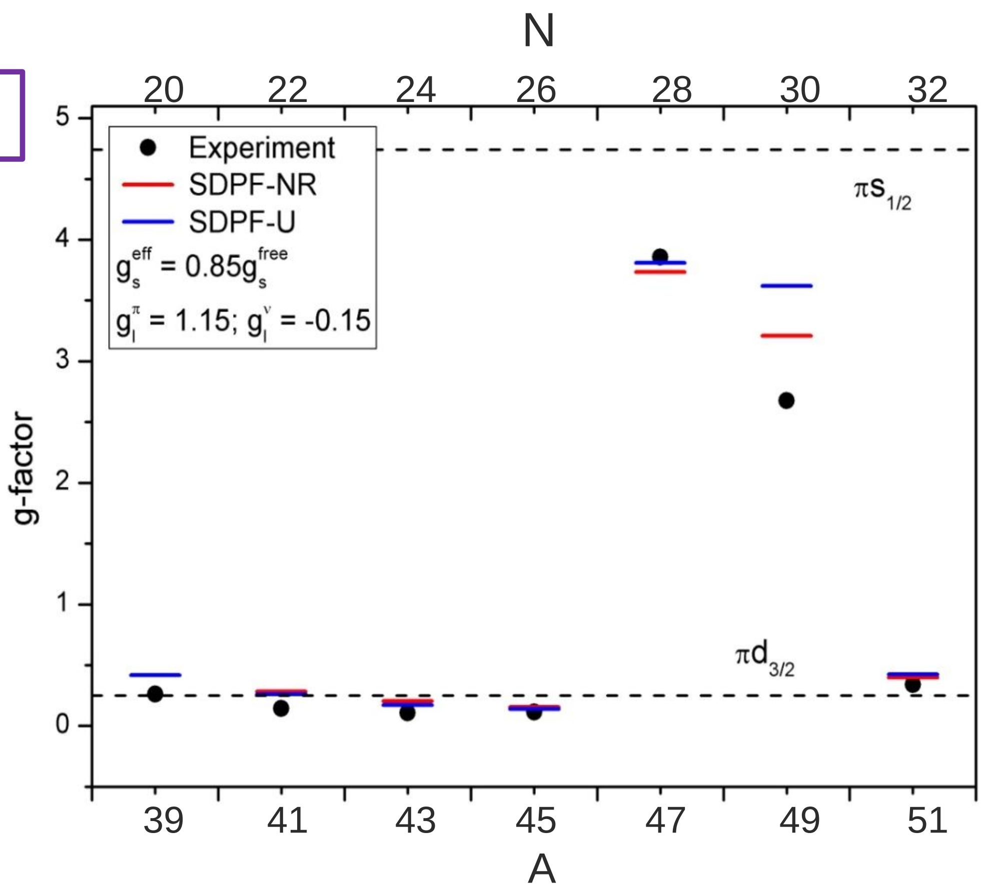
Magnetic moment of odd-K (odd-even) isotopes

$$g = \frac{\mu}{I}$$



Spin determination

- ^{49}K:
  3 peaks => I = 1/2

- ^{51}K:
  4 peaks => I > 1/2
  I = 3/2 from intensities ratio

- - - - Effective single-particle *g* factor

- ^{47}K: ~13% mixing with $\pi d_{3/2}^{-1} - \nu(pf)$

- ^{49}K: ~20% from SDPF-NR and ~15% from SDPF-U
  more mixing is needed

Published in PRL 110, 172503 (2013)

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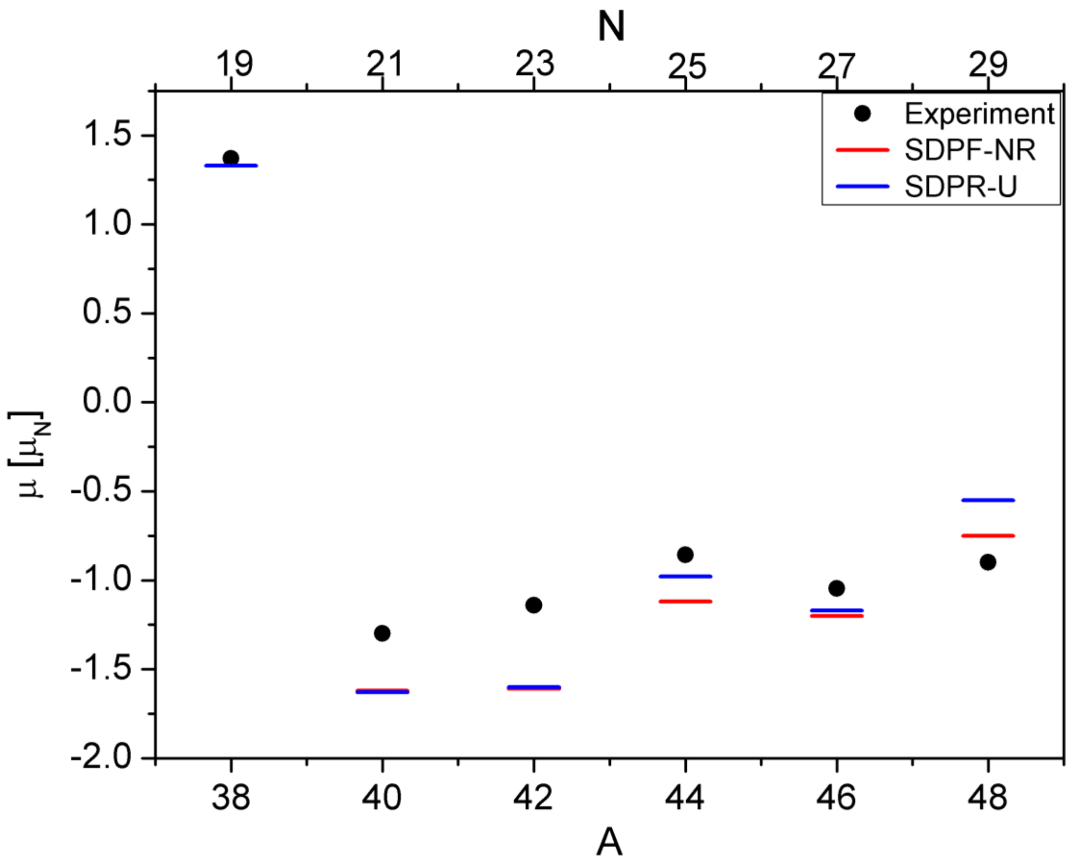
Magnetic moment for even-K (odd-odd) isotopes



Spin determination

- ^{48}K:

I = 1 from intensities ratio

- ^{50}K:

I = 0 => single peak

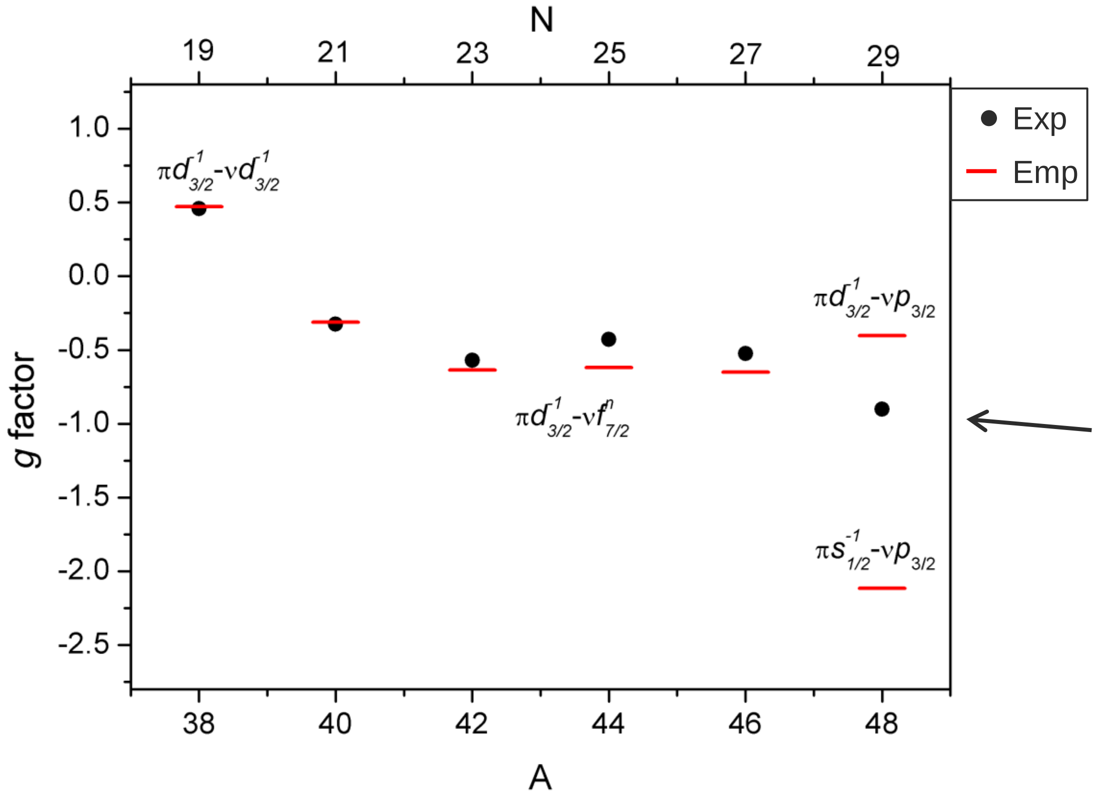
Empirical magnetic moments

- Additivity rule for odd-odd isotopes:

$$g(I) = \frac{g(j_\pi)+g(j_\nu)}{2} + \frac{g(j_\pi)-g(j_\nu)}{2}\frac{j_\pi(j_\pi+1)-j_\nu(j_\nu+1)}{I(I+1)}$$

$g(j_\pi)$: odd-even K isotopes

$g(j_\nu)$: even-odd Ca isotopes (Z = 20)



^{48}K: mixed configuration

Conclusions

- For the first time, the hyperfine spectra for $^{48-51}K$ were obtained

- The ground state spins were deduced for $^{48-51}K$

- From the magnetic moments (*g* factors) => the composition of the wave function

- The gap between proton $1d_{3/2}$ and $2s_{1/2}$ orbits reaches a minimum around $N = 29$ and again increases towards the more neutron-rich K isotopes

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COLLAPS collaboration

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Thank you for your attention!

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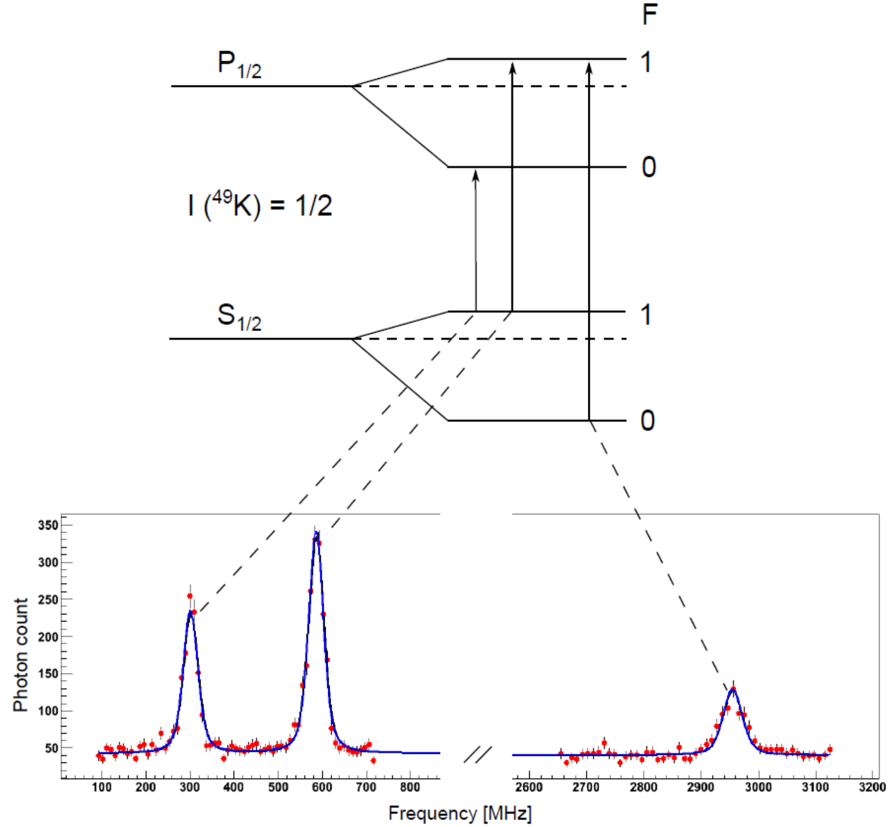
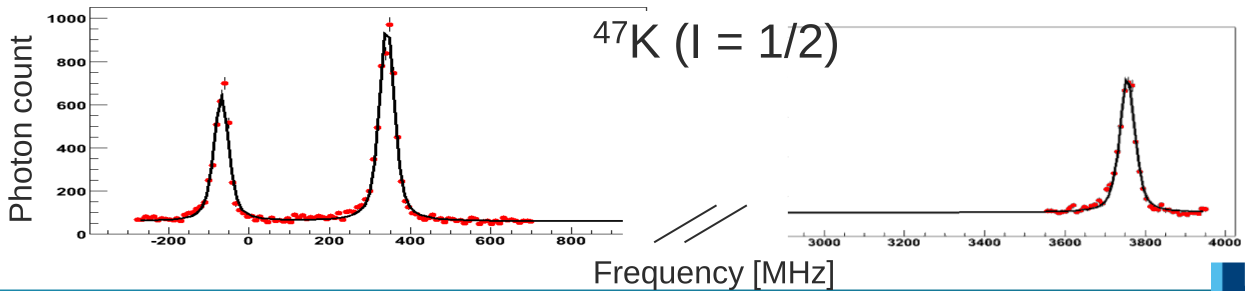
Spin determination of ^{49}K

3 peaks => *I* = 1/2





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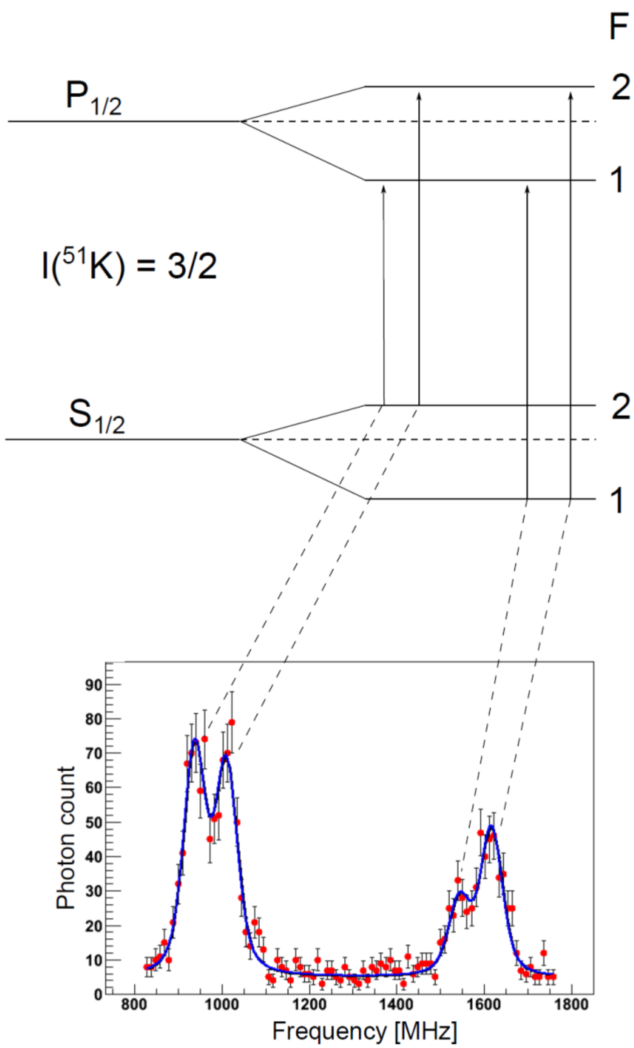
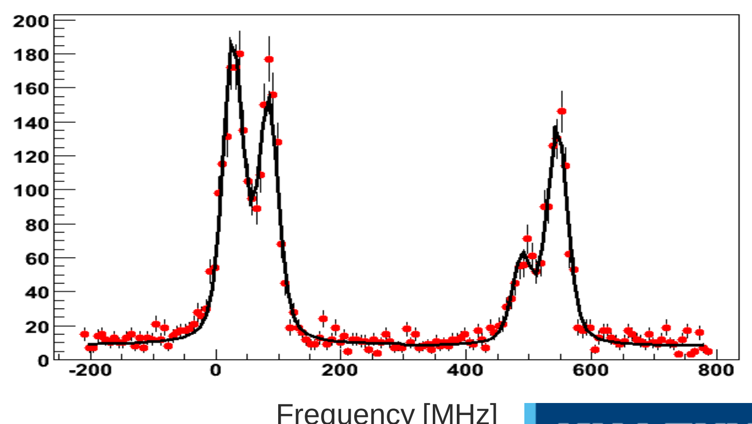
Spin determination of ^{51}K



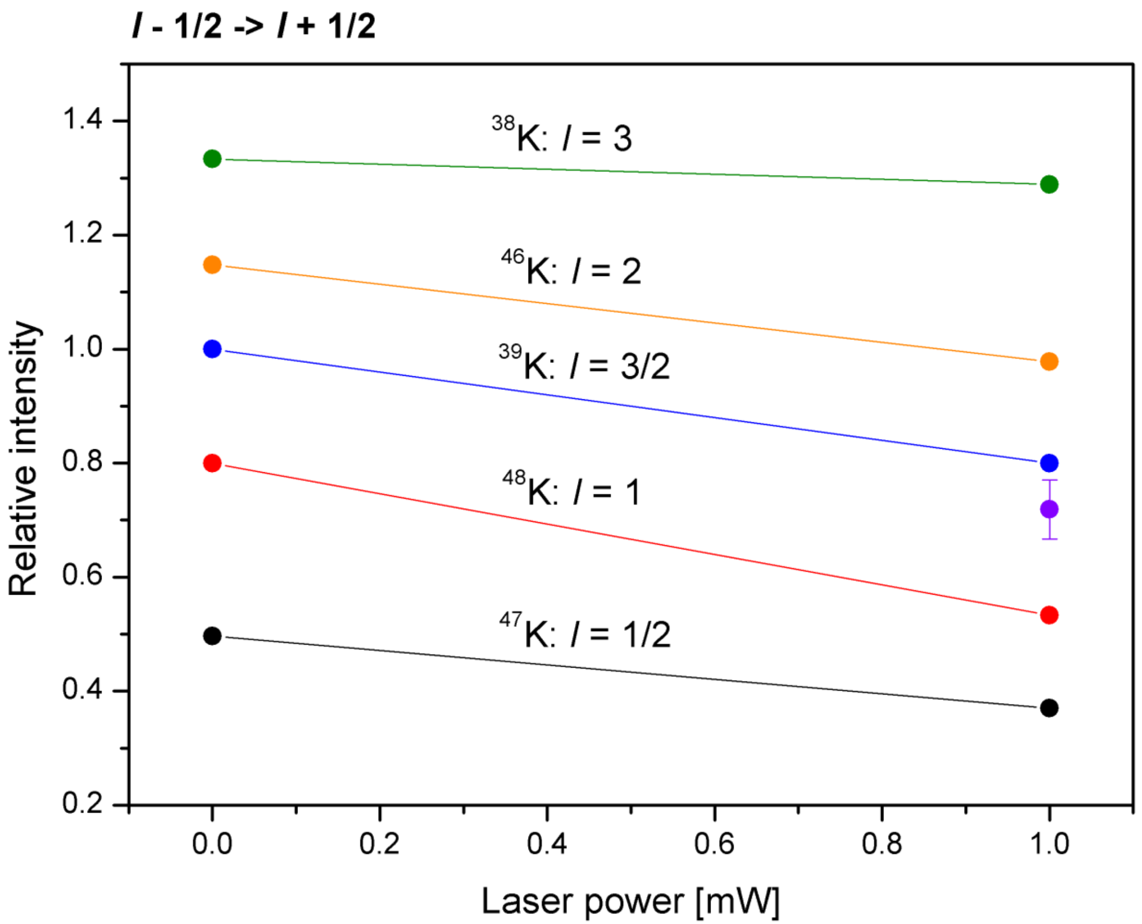
4 peaks => $I > 1/2$

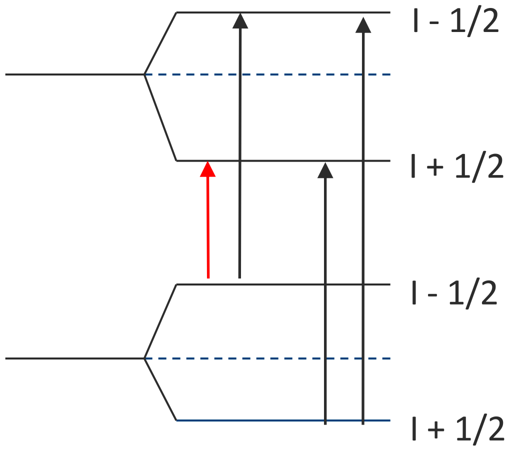
$I = 3/2$ from intensities ratio

^{39}K ($I = 3/2$)

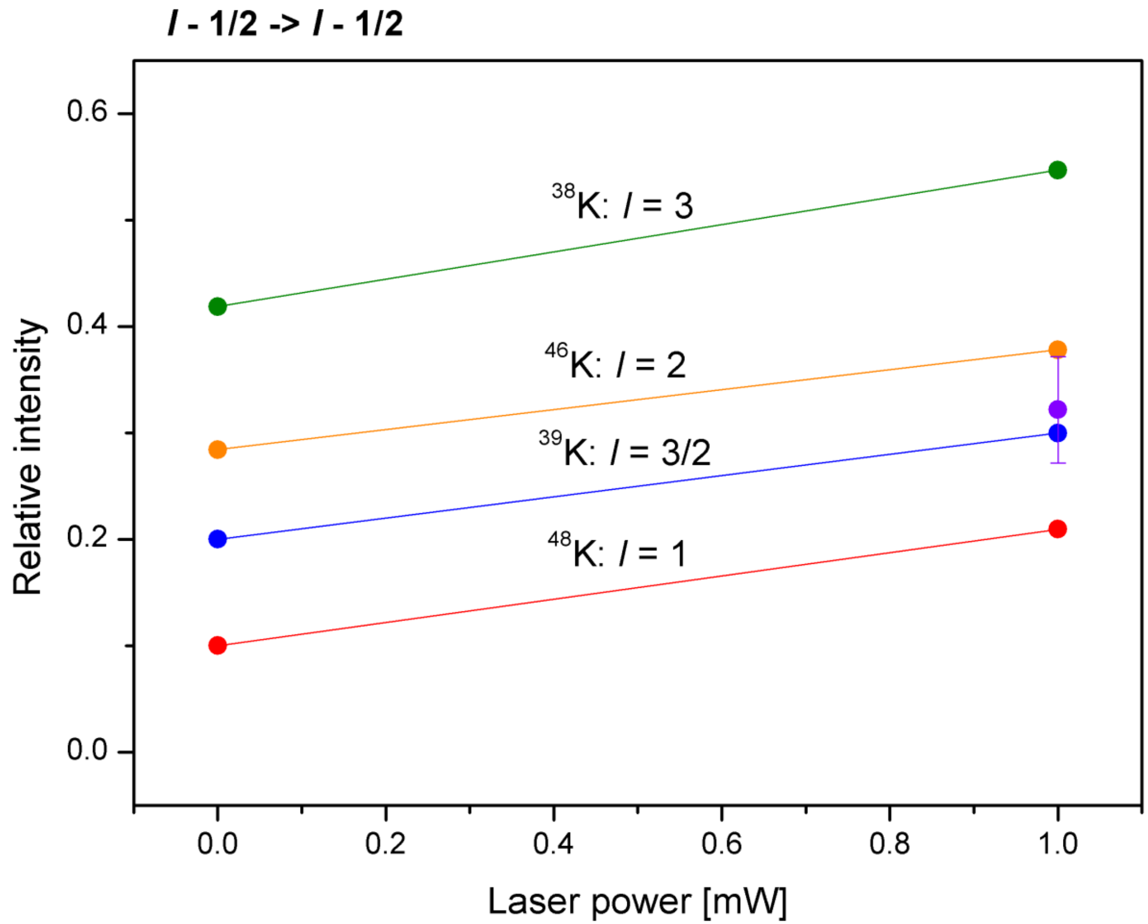


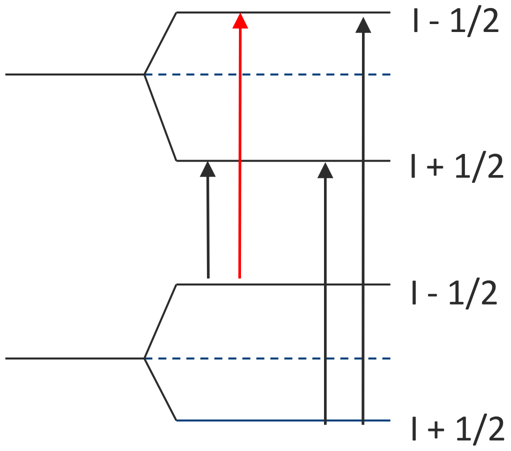
Spin determination of ^{51}K



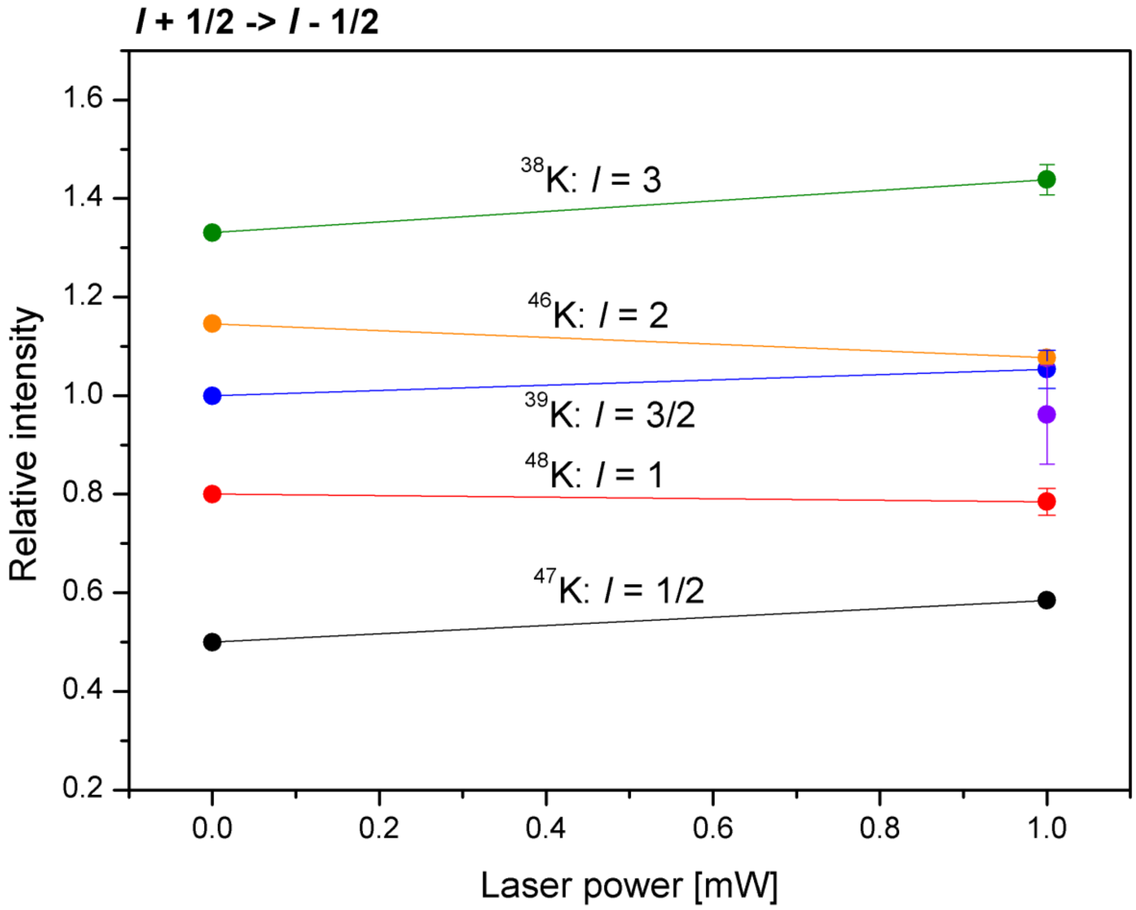


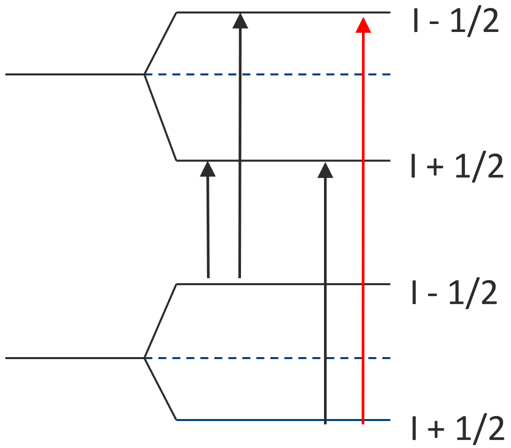
Spin determination of ^{51}K





Spin determination of ^{51}K





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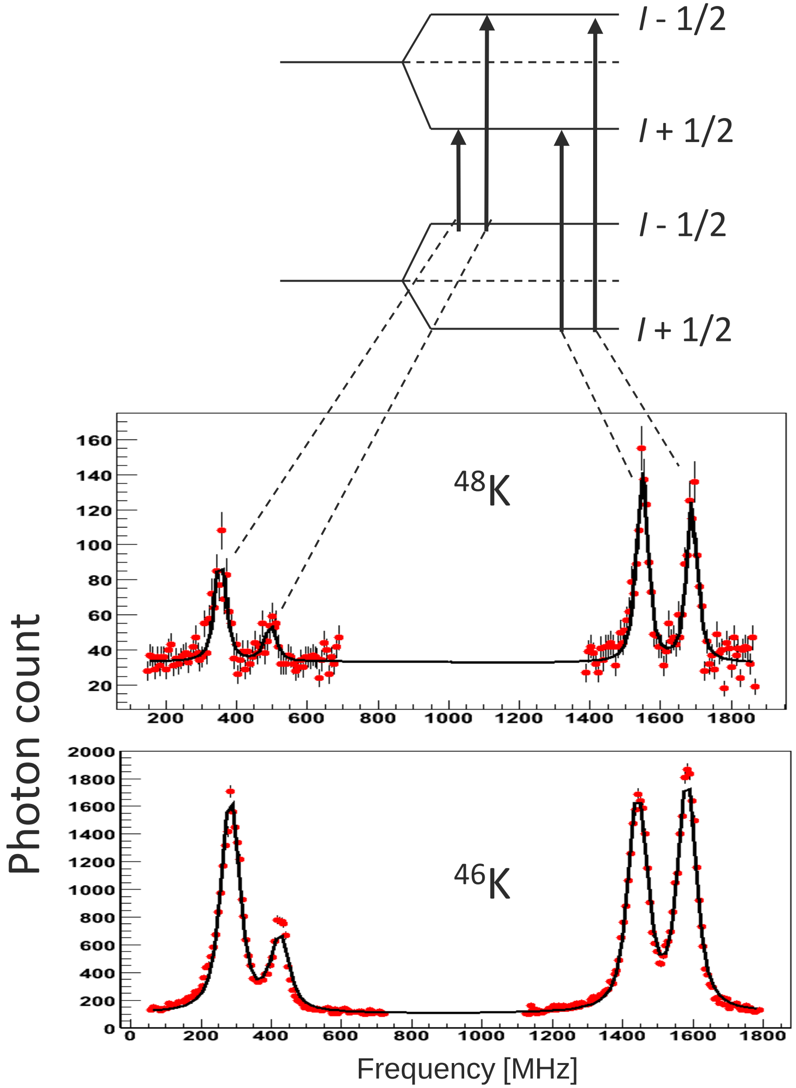
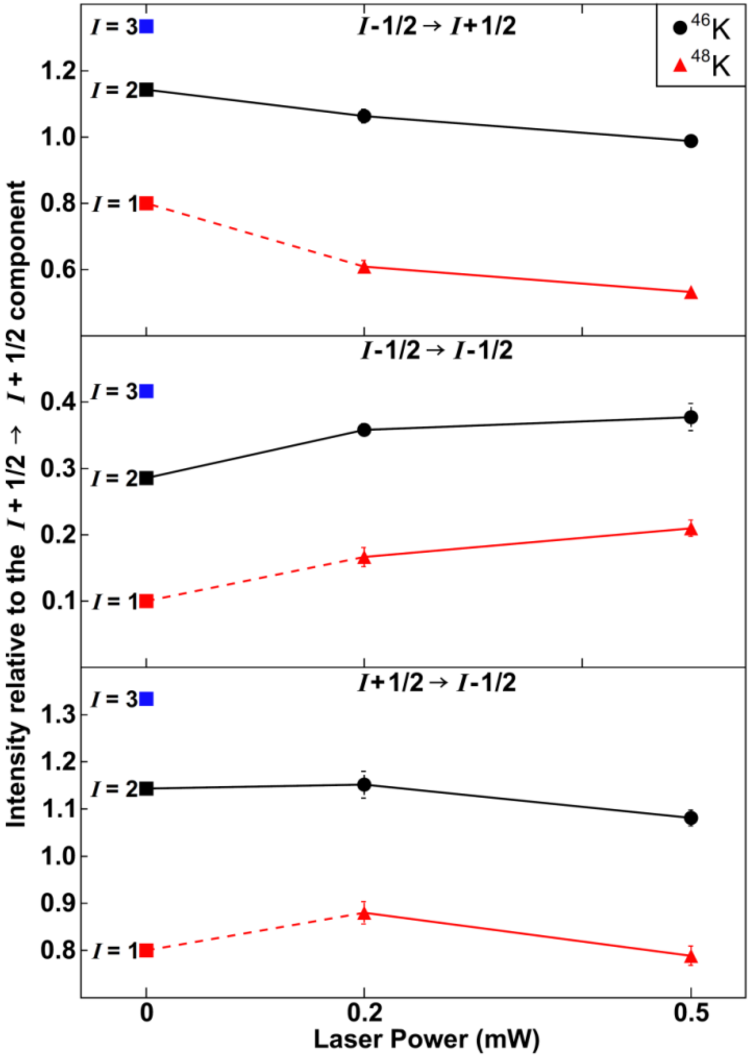
Spin determination of ^{48}K





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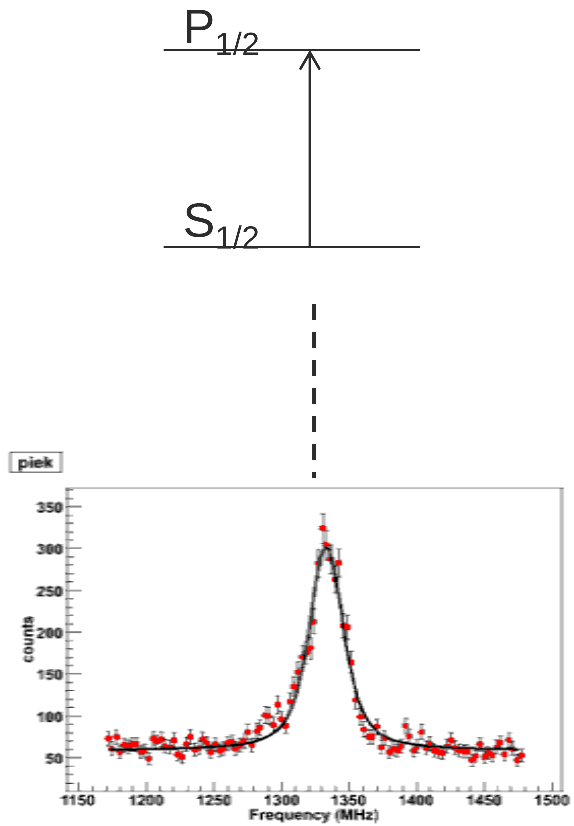
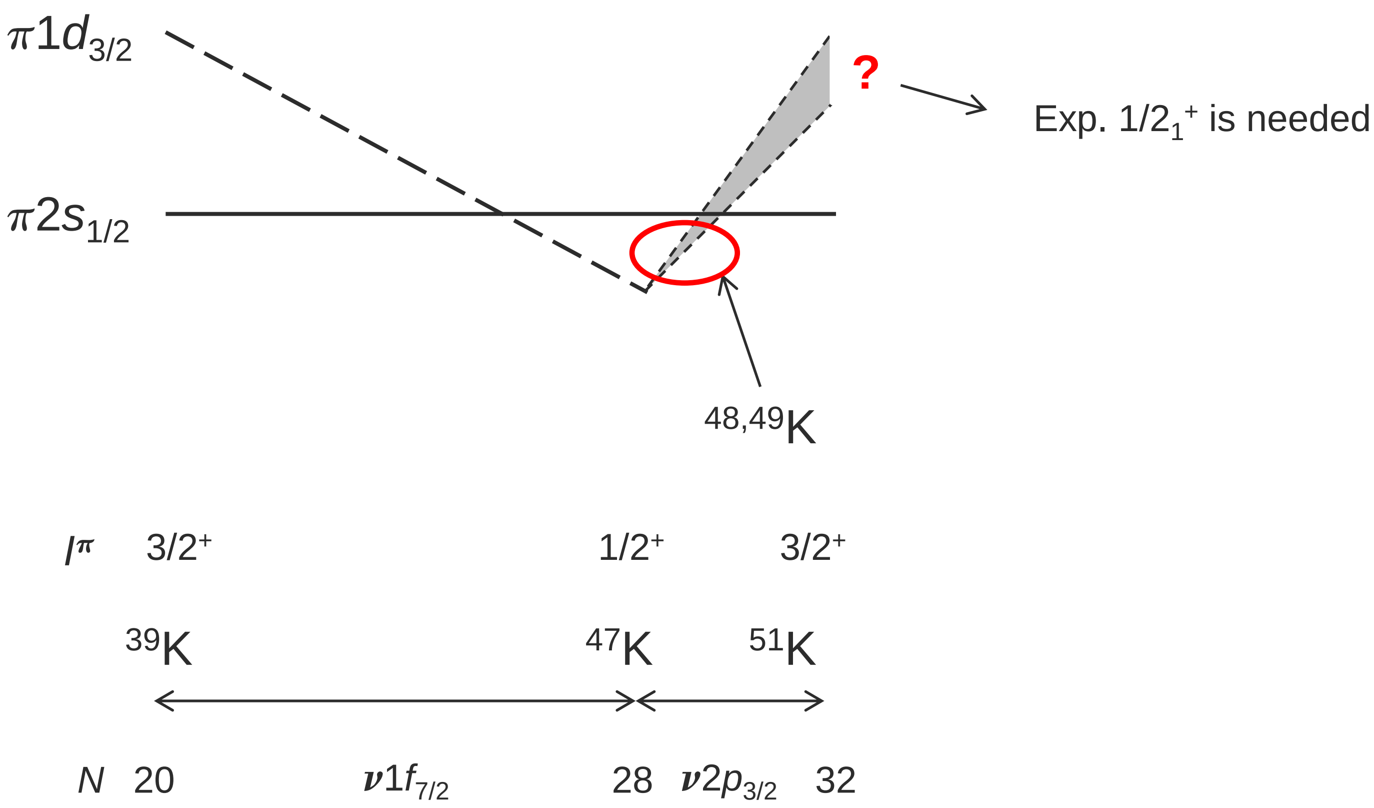
Spin determination of ^{50}K

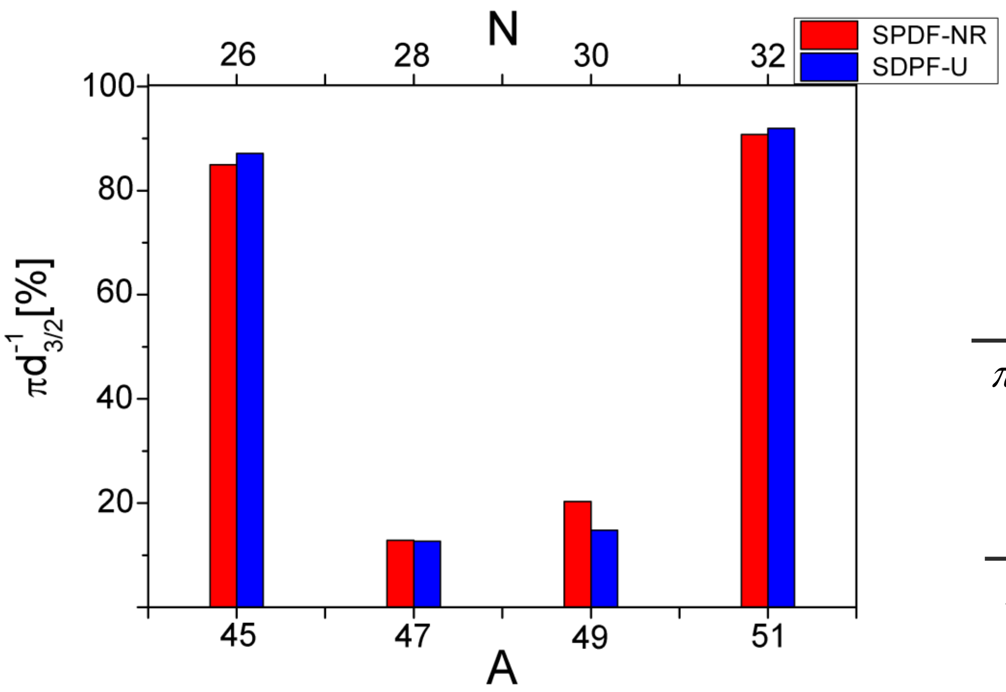
I = 0 => single peak



Monopole interaction



Composition of the wave function of odd-K



^{47}K	SDPF-NR	SDPF-U
$\pi d^{-1}_{3/2} \otimes \nu(fp)$	13%	13%

^{49}K	SDPF-NR	SDPF-U
$\pi d^{-1}_{3/2} \otimes \nu(fp)$	20%	15%

- ^{49}K: more mixing is needed (~25%)

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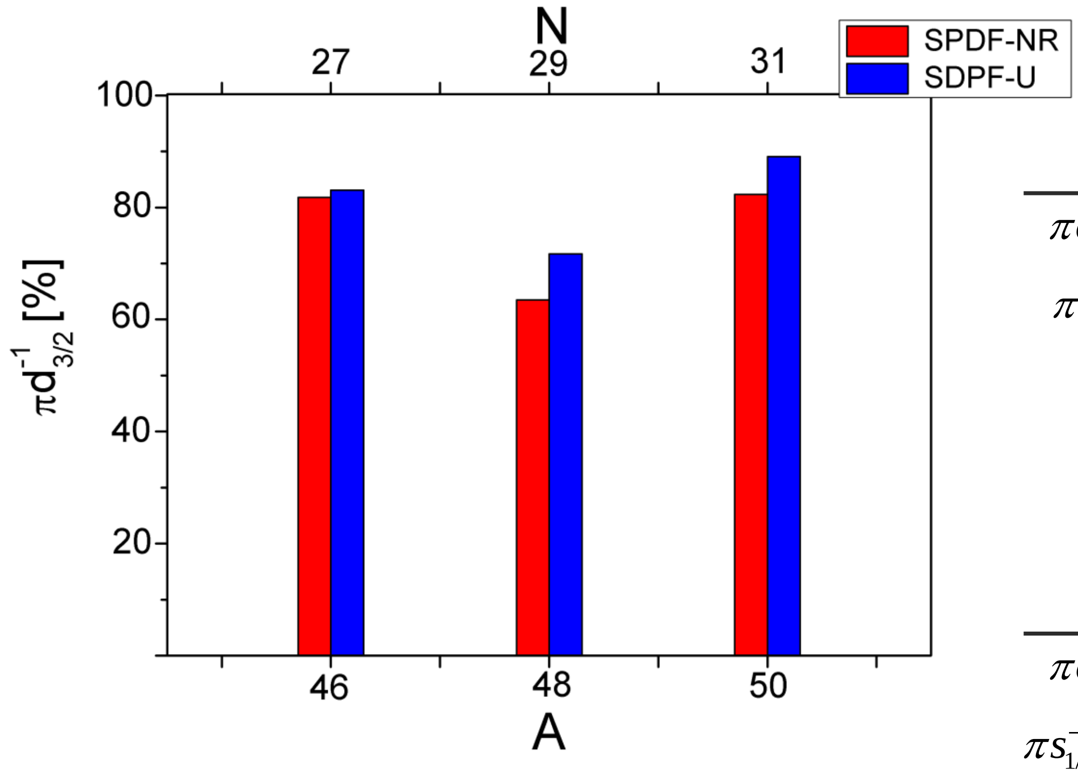
Composition of the wave function of even-K



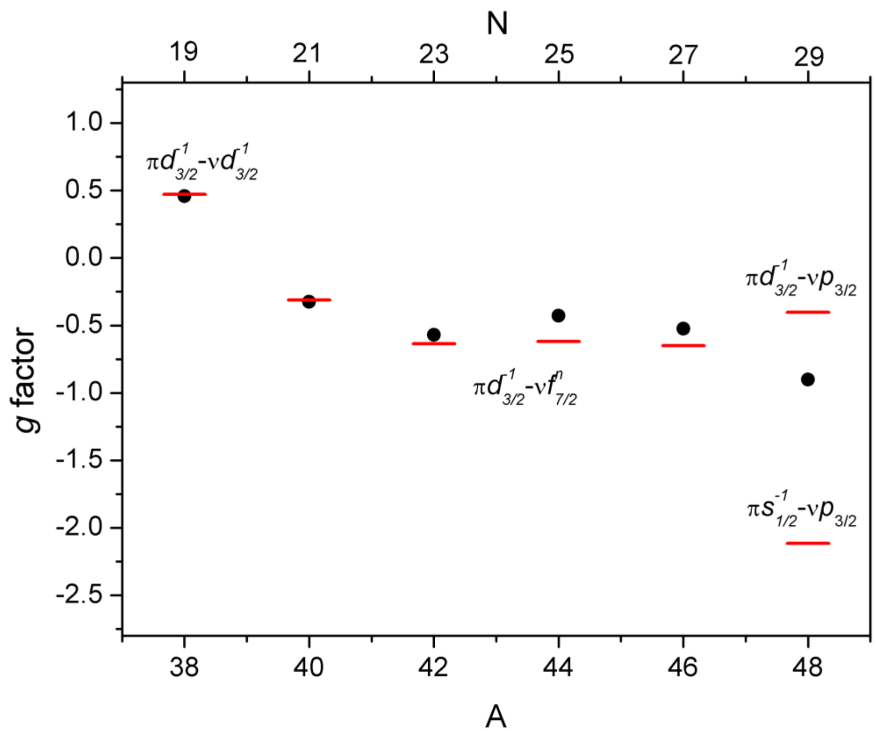
^{48}K	SDPF-NR	SDPF-U
$\pi d_{3/2}^{-1} \otimes \nu p_{3/2}$	38%	51%
$\pi s_{1/2}^{-1} \otimes \nu p_{3/2}$	16%	14%

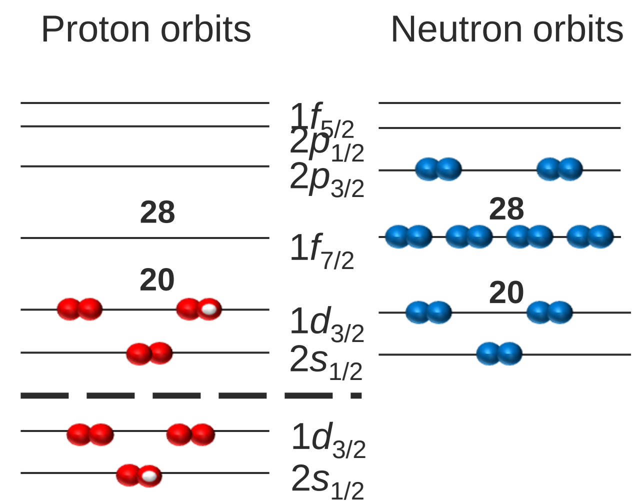
^{50}K	SDPF-NR	SDPF-U
$\pi d_{3/2}^{-1} \otimes \nu p_{3/2}^{-1}$	63%	75%
$\pi s_{1/2}^{-1} \otimes \nu p_{3/2}^{2} p_{1/2}$	7%	$> 5\%$

Empirical magnetic moments

- Additivity rule for odd-odd isotopes:

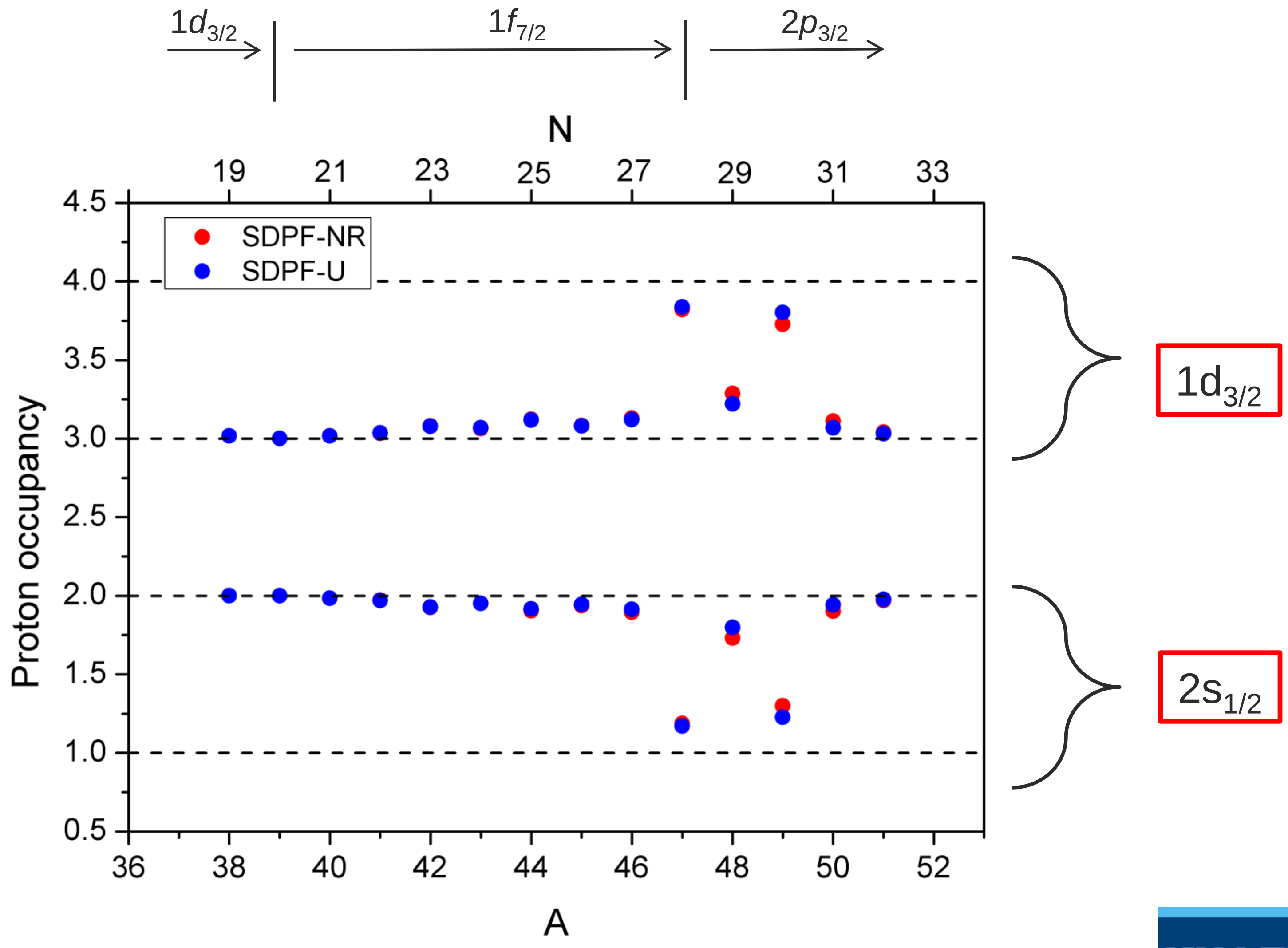
$$g(I) = \frac{g(j_\pi)+g(j_\nu)}{2} + \frac{g(j_\pi)-g(j_\nu)}{2}\,\frac{j_\pi(j_\pi+1)-j_\nu(j_\nu+1)}{I(I+1)}$$





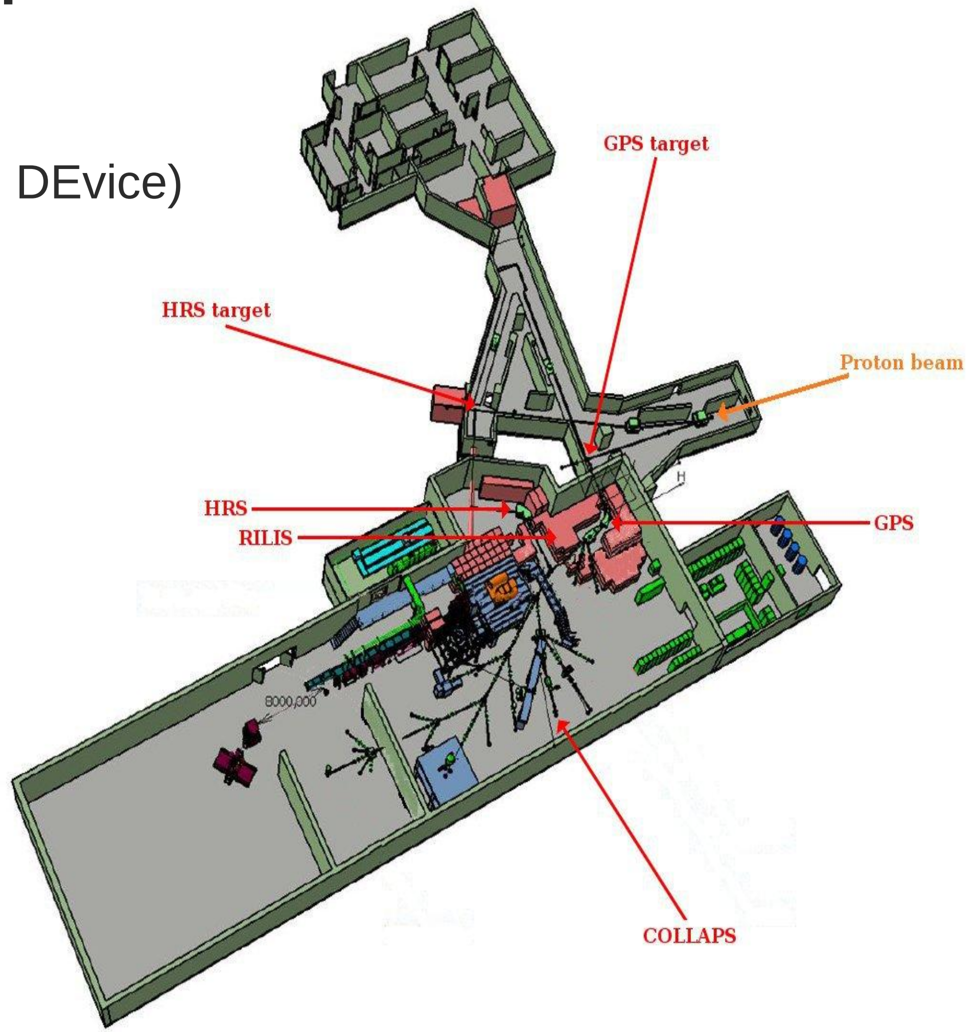
Isotope	I^π	configuration	g_{emp}	used isotopes
^{38}K	3^+	$\pi 1d^{-1}_{3/2} \otimes \nu 1d^{-1}_{3/2}$	+0.47	(^{39}K; ^{39}Ca)
^{40}K	4^-	$\pi 1d^{-1}_{3/2} \otimes \nu 1f_{7/2}$	-0.31	(^{39}K; ^{41}Ca)
^{42}K	2^-	$\pi 1d^{-1}_{3/2} \otimes \nu 1f^{3}_{7/2}$	-0.64	(^{41}K; ^{43}Ca)
^{44}K	2^-	$\pi 1d^{-1}_{3/2} \otimes \nu 1f^{5}_{7/2}$	-0.62	(^{43}K; ^{45}Ca)
^{46}K	2^-	$\pi 1d^{-1}_{3/2} \otimes \nu 1f^{-1}_{7/2}$	-0.65	(^{45}K; ^{47}Ca)
^{48}K	1^-	$\pi 1d^{-1}_{3/2} \otimes \nu 2p_{3/2}$	-0.40	(^{45}K; ^{49}Ca)
^{48}K	1^-	$\pi 2s^{-1}_{1/2} \otimes \nu 2p_{3/2}$	-2.11	(^{47}K; ^{49}Ca)

Occupation


1d3/2
1f7/2
2p3/2
N
19
21
23
25
27
29
31
33
SDPF-NR
SDPF-U
Proton occupancy
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
36
38
40
42
44
46
48
50
52
A
1d3/2
2s1/2

Setup – Ion beam

- ISOLDE (Isotope Separator On-Line DEvice)
- Protons (1.4GeV) on UC_x target
- Ionization by Surface Ion Source
- Ions accelerated up to 60 keV
- HRS (High Resolution Separation)



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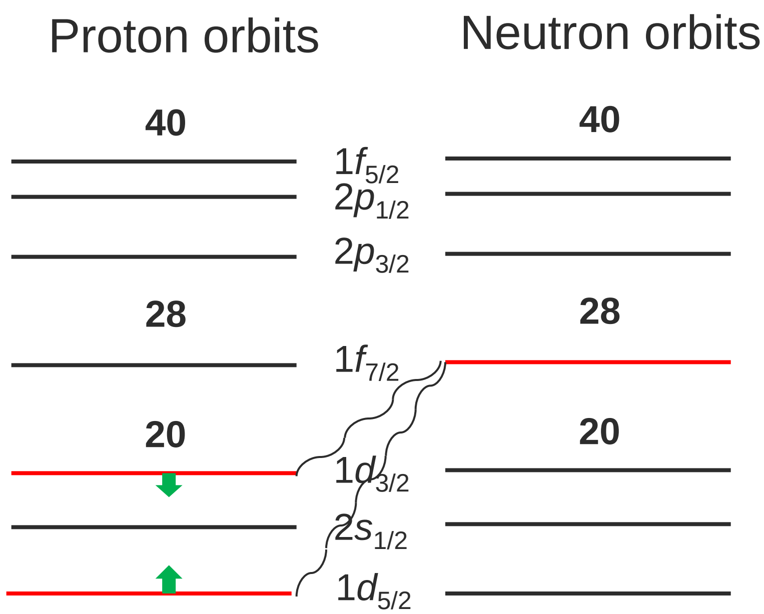
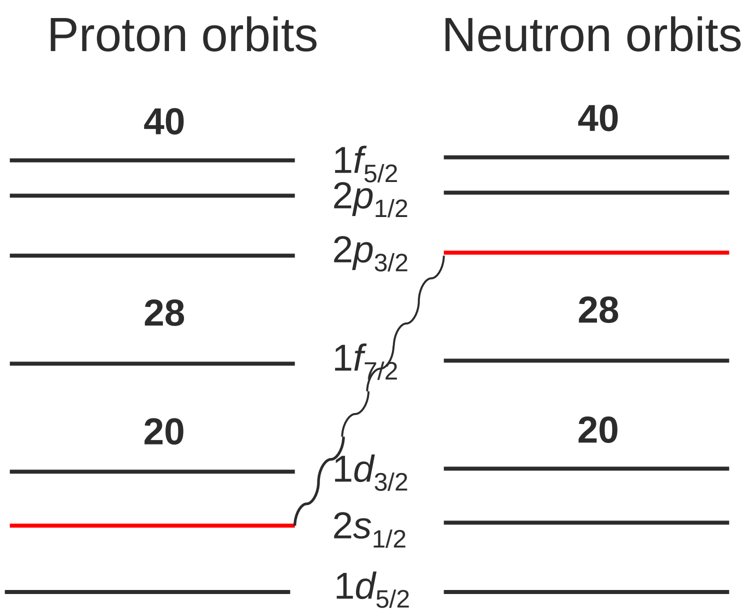
Tensor part



Central part



- $n = n`$ and $l = l`$ => maximal overlap of the WF
- Spin-dependent: $j_> = l + 1/2$ and $j_< = l - 1/2$
($j_>$ and $j_<$) is stronger than ($j_>$ and $j_>$) or ($j_<$ and $j_<$)

Magnetic moments - results

Isotope	I^π	μ_{exp}	$\mu_{SDPF-NR}$	$\pi 1d_{3/2}^{-1}$ [%]	μ_{SDPF-U}	$\pi 1d_{3/2}^{-1}$ [%]	μ_{lit}	Reference
^{39}K	$3/2^+$	+0.3917 (5) [12]	+0.65	95%	+0.65	95%	+0.3914662 (3)	[29]
^{41}K	$3/2^+$	-	+0.42	92%	+0.38	92%	+0.2148701 (2)	[29]
^{43}K	$3/2^+$	-	+0.27	88%	+0.22	88%	+0.1633 (8)[a]	[27]
^{45}K	$3/2^+$	-	+0.26	85%	+0.24	87%	+0.1734 (8)[a]	[27]
^{47}K	$1/2^+$	+1.92924 (11) [58]	+1.86	13%	+1.91	13%	+1.933(9)[a]	[27]
^{49}K	$1/2^+$	+1.3386 (8) [40]	+1.63	20%	+1.82	15%	-	-
^{51}K	$3/2^+$	+0.5129 (22) [15]	+0.59	91%	+0.63	92%	-	-

Isotope	I^π	μ_{exp}	$\mu_{SDPF-NR}$	μ_{SDPF-U}	μ_{lit}	Reference
^{38}K	3^+	+1.3703 (6) [41]	+1.33	+1.33	+1.371 (6)[a]	[27]
^{40}K	4^-	-	-1.62	-1.63	-1.2964 (4)[b]	[31]
^{42}K	2^-	-1.1393 (3) [34]	-1.61	-1.60	-1.14087 (20)[b]	[28]
^{44}K	2^-	-0.8569 (5) [26]	-1.12	-0.98	-0.856 (4)[a]	[27]
^{46}K	2^-	-1.0464 (5) [31]	-1.20	-1.17	-1.051 (6)[a]	[27]
^{48}K	1^-	-0.8997 (3) [27]	-0.75	-0.55	-	-

[27] F. Touchard *et al.*, Phys. Lett. B **108**, 169 (1982).
[28] Y. W. Chan, V. W. Cohen, and H. B. Silsbee, Phys. Rev. **184**, 1102 (1969).
[29] A. Beckmann, K. D. Böklen, and D. Elke, Zeitschrift für Physik A Hadrons and Nuclei **270**, 173 (1974).
[31] J. T. Eisinger, B. Bederson, and B. T. Feld, Phys. Rev. **86**, 73 (1952).

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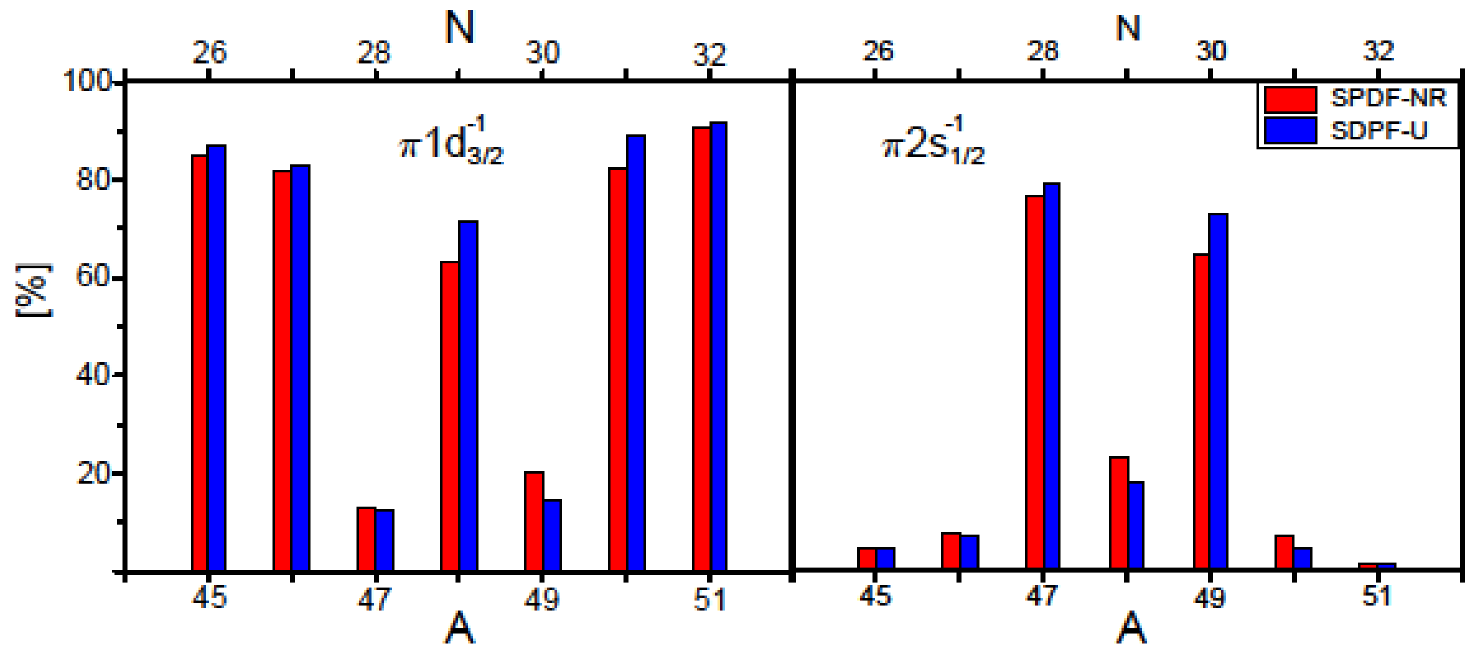
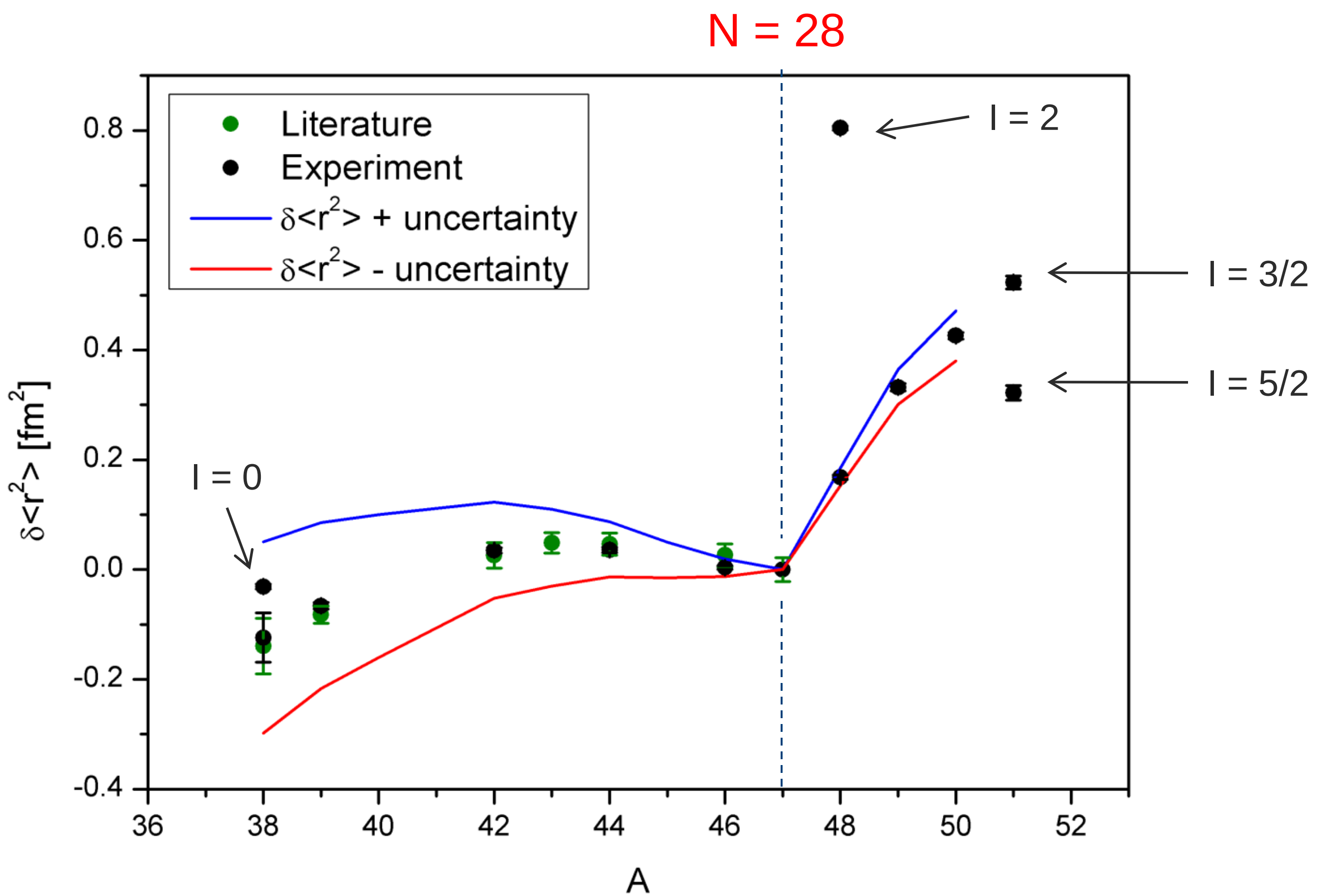
Isotope	I^{π}	SDPF-NR configuration $(\pi \otimes \nu)$	SDPF-NR [%]	SDPF-U configuration $(\pi \otimes \nu)$	SDPF-U [%]
^{48}K	1^-	$1d^{-1}_{3/2} \otimes 2p_{3/2}$	38	$1d^{-1}_{3/2} \otimes 2p_{3/2}$	51
		$2s^{-1}_{1/2} \otimes 2p_{3/2}$	16	$2s^{-1}_{1/2} \otimes 2p_{3/2}$	14
		$1d^{-1}_{3/2} \otimes 1f^{-1}_{7/2}2p^{2}_{3/2}$	14	$1d^{-1}_{3/2} \otimes 1f^{-1}_{7/2}2p^{2}_{3/2}$	11
		$1d^{-1}_{3/2} \otimes 1f^{6}_{7/2}2p^{-1}_{3/2}$	5	$1d^{-1}_{3/2} \otimes 1f^{8}_{7/2}2p_{1/2}$	3
		$2s^{-1}_{1/2} \otimes 1f^{-1}_{7/2}2p^{2}_{3/2}$	4	$2s^{-1}_{1/2} \otimes 1f^{-1}_{7/2}2p^{2}_{3/2}$	3
^{50}K	0^-	$1d^{-1}_{3/2} \otimes 2p^{-1}_{3/2}$	63	$1d^{-1}_{3/2} \otimes 2p^{-1}_{3/2}$	75
		$2s^{-1}_{1/2} \otimes 2p^{2}_{3/2}2p_{1/2}$	7	$1d^{-1}_{3/2} \otimes 2p^{2}_{3/2}2p_{1/2}$	4
		$1d^{-1}_{3/2} \otimes 1f^{-1}_{7/2}2p^{-1}_{3/2}2p_{1/2}$	6	$2s^{-1}_{1/2} \otimes 2p^{2}_{3/2}2p_{1/2}$	4
		$1d^{-1}_{3/2} \otimes 2p^{2}_{3/2}2p_{1/2}$	5	$1d^{-1}_{3/2} \otimes 1f^{6}_{7/2}2p^{-1}_{3/2}$	3
		$1d^{-1}_{3/2} \otimes 1f^{6}_{7/2}2p^{-1}_{3/2}1f^{2}_{5/2}$	4	$1d^{-1}_{3/2} \otimes 1f^{-1}_{7/2}2p^{-1}_{3/2}2p_{1/2}$	2

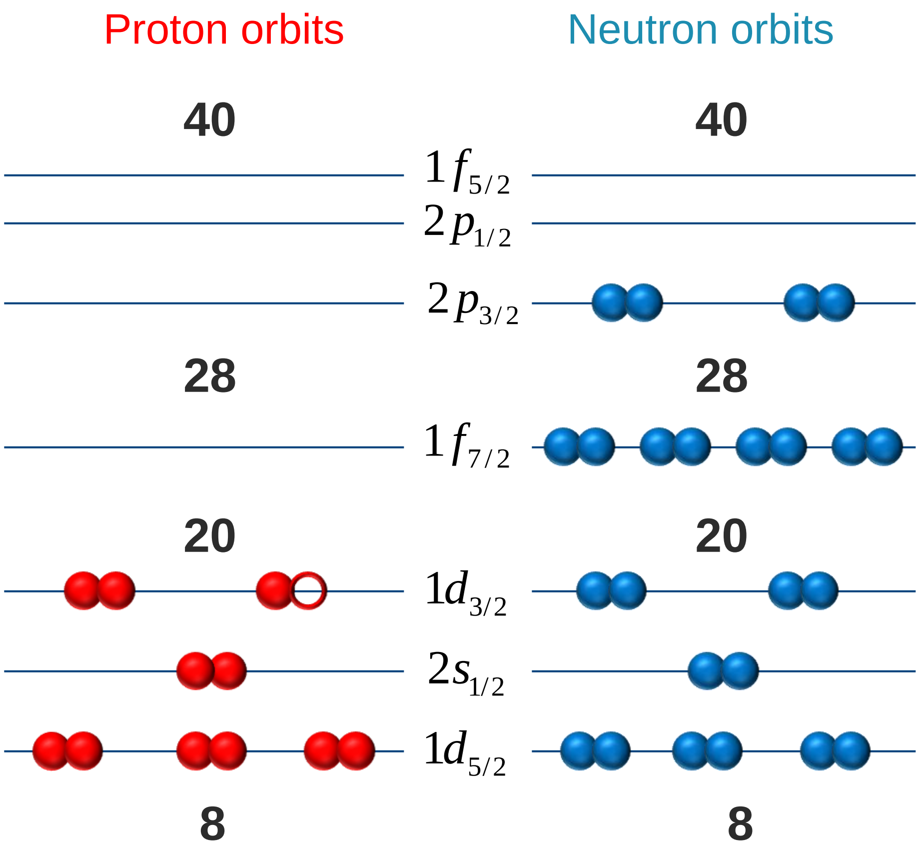
Composition of the wave function



Charge radii

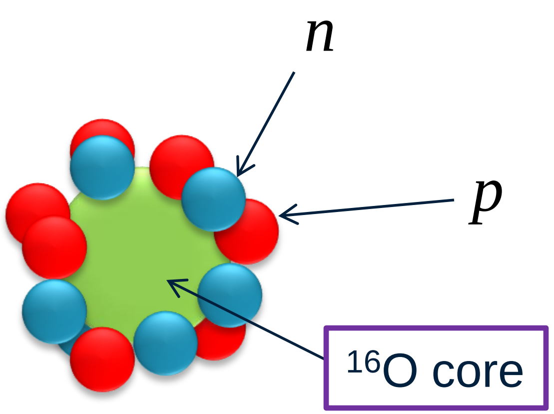


Theoretical model



Effective interactions:

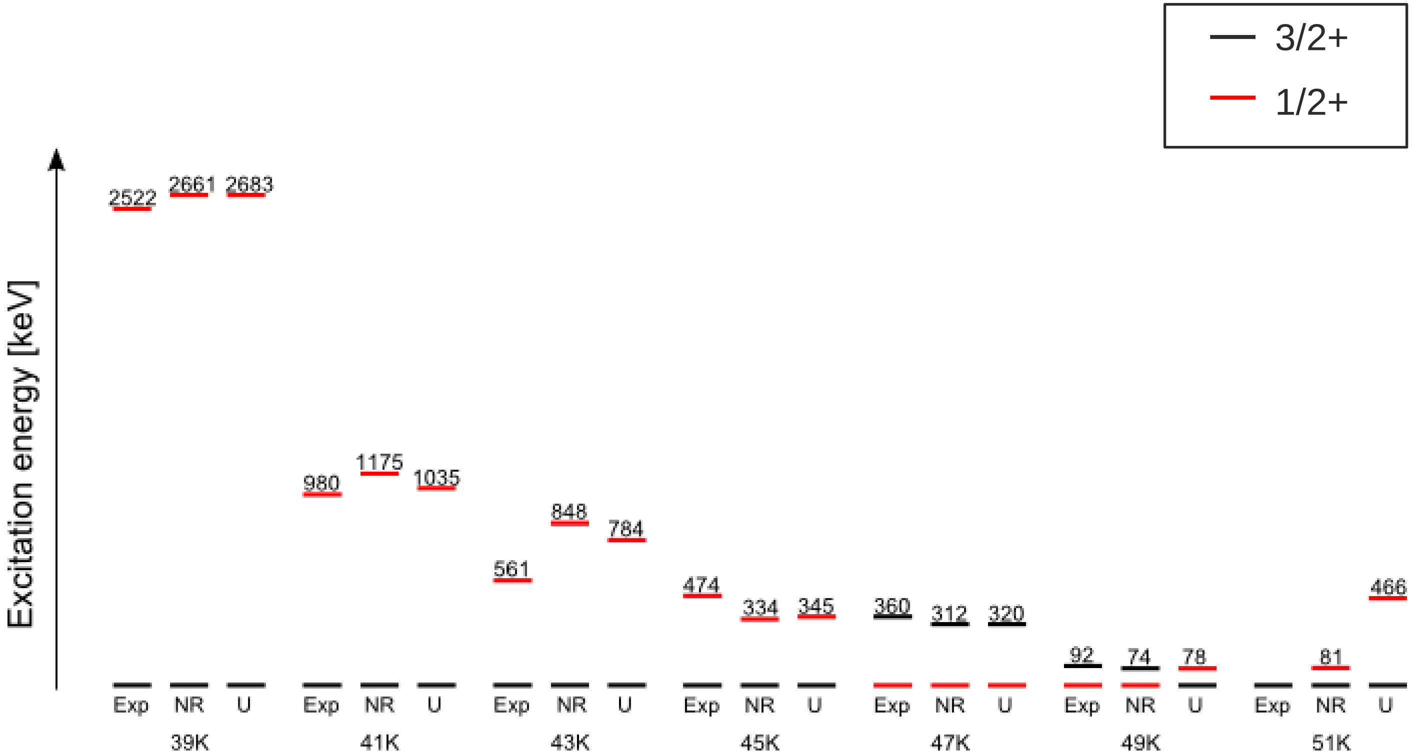
SDPF-NR[1] SDPF-U[2]



$^{47}K \rightarrow {}^{16}O + 11\pi + 20\nu$

[1] J. Retamosa *et al.*, Phys. Rev. C 55, 1266 (1997)
S. Nummela *et al.*, Phys. Rev. C 64, 054313 (2001)

[2] F. Nowacki and A. Poves, Phys. Rev. C 79, 014310 (2009): ^{35}Si (Z = 14), ^{47}Ar (Z = 18) and ^{41}Ca (Z = 20)



3/2+
1/2+
Excitation energy [keV]
2522
2661
2683
980
1175
1035
561
848
784
474
334
345
360
312
320
92
74
78
81
466
Exp NR U Exp NR U Exp NR U Exp NR U Exp NR U Exp NR U Exp NR U
39K
41K
43K
45K
47K
49K
51K

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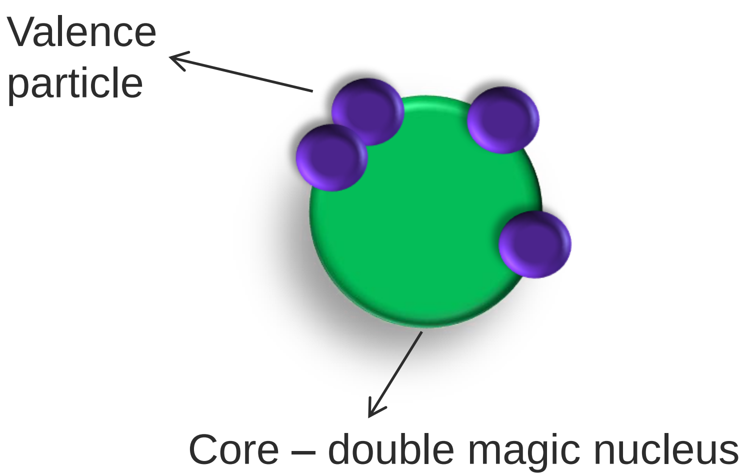
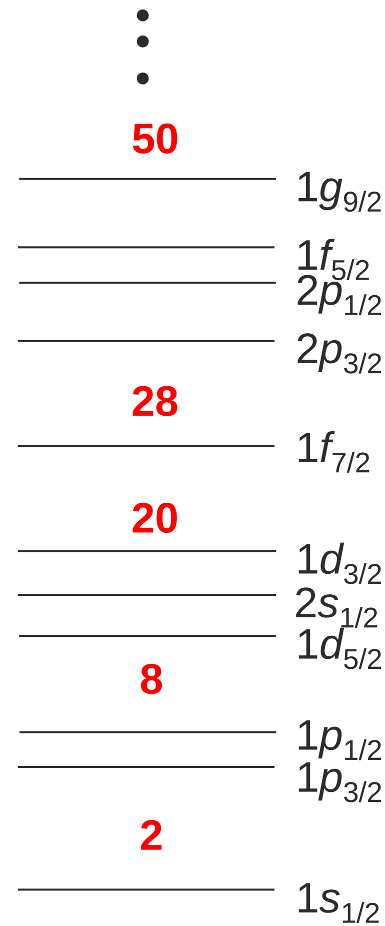
Motivation

- Shell model:
  - Orbits (*nlj*) with max. 2*j*+1 particles
  - Shell gaps
  - Magic numbers





- “Exotic” nuclei (large *N*/*Z*): shell evolution

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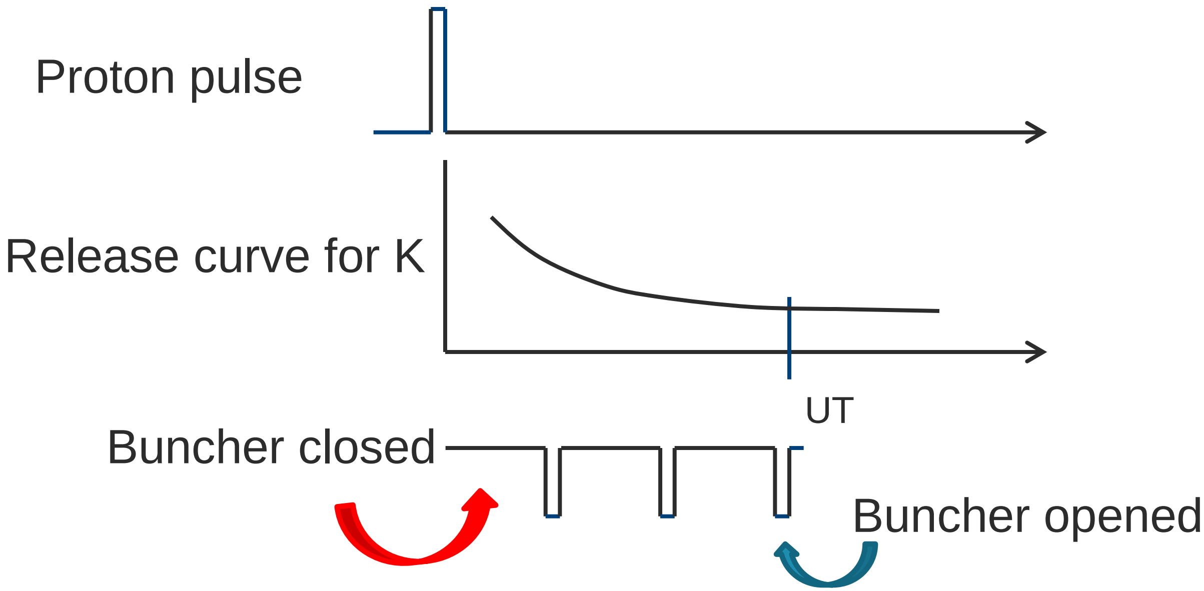
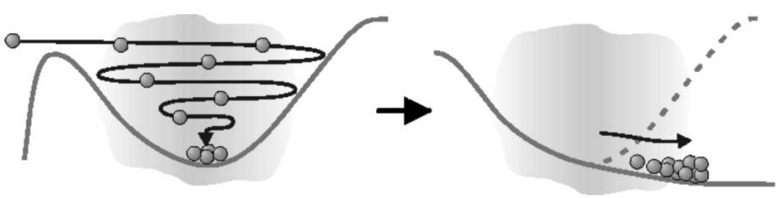
Collinear Laser Spectroscopy





- Accumulation Time (AT): 90 ms
- Release Time (RT): 6 µs
- Useful Time (UT): 3*AT

new lens geometry + 4 PMTs

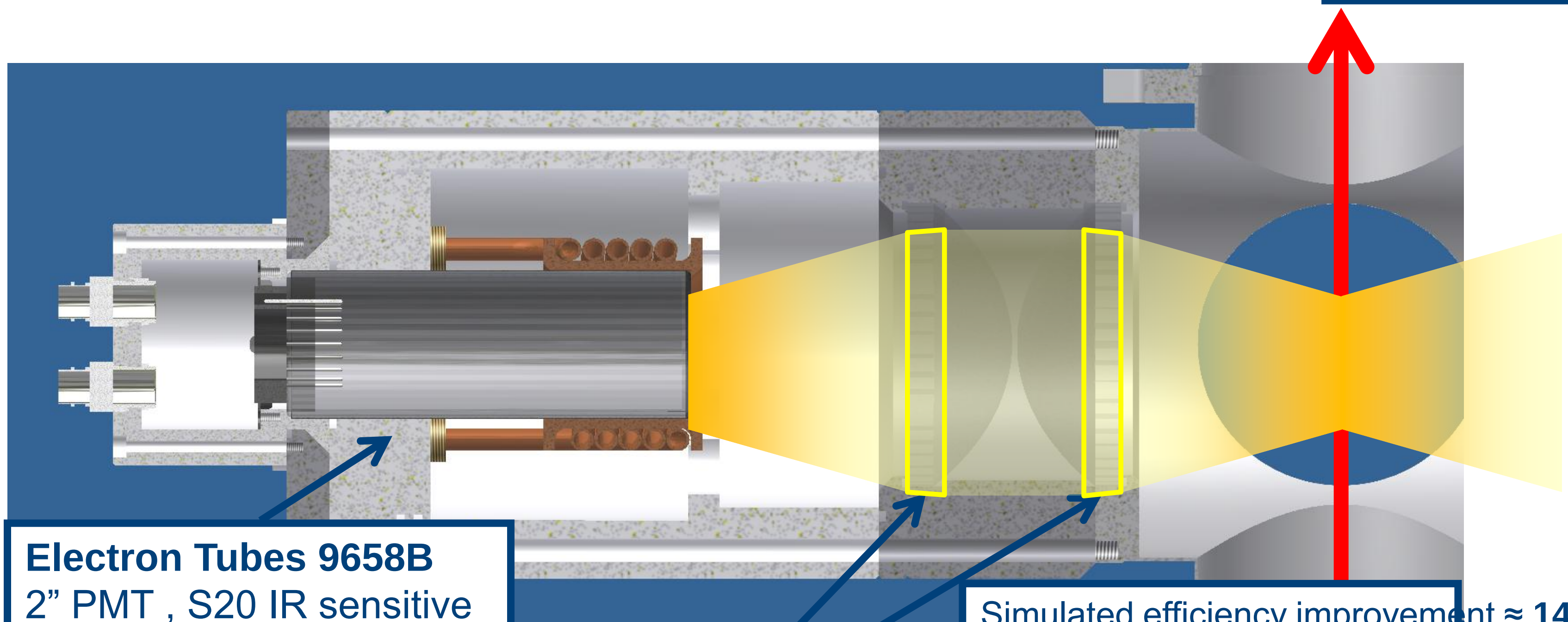
↓

Efficiency: 10 times improved

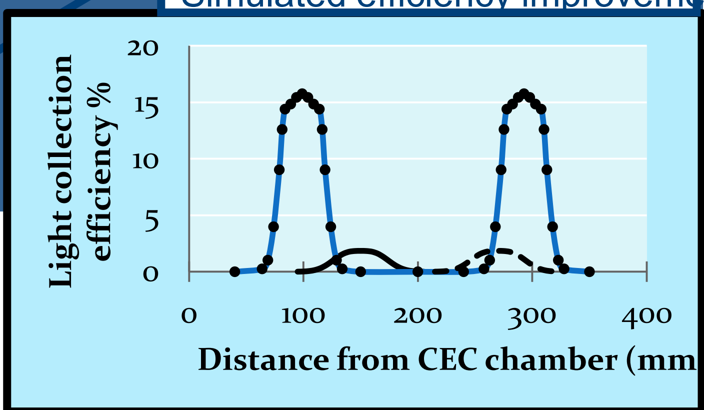
G. Bollen, Lect. Notes Phys. 651, 169-210 (2004)

Optical detection efficiency for K (red light) <u>improved by factor 10</u>

<u>+ background photon detection reduced by 50% !</u>



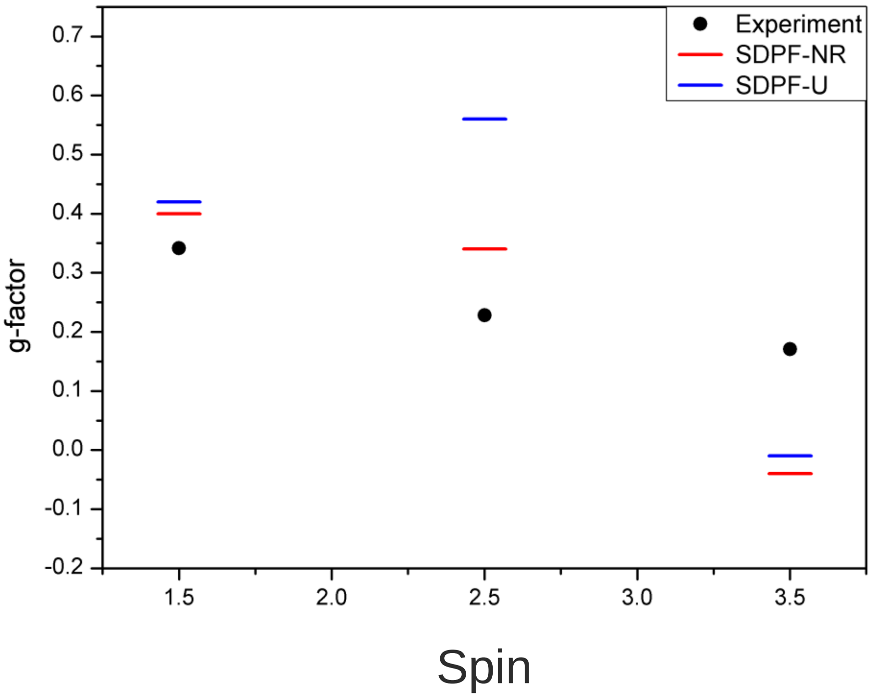
Simulated efficiency improvement ≈ **14x**



Design: Mark Bissell, NIM, in preparation

Spin	g_{exp}	SDPF-NR	SDPF-U
3/2	0.3419(15)	0.40 [E = 0]	0.42 [E = 0]
5/2	0.2279(11)	0.34 [E = 1725]	0.56 [E = 2018]
7/2	0.1710(8)	-0.04 [E = 1793]	-0.01 [E = 2040]

E in keV



References:

- ^{39}K: A. Beckmann *et al*., Z. Physics, Volume 270 (1974) 173-186
- Radii: A-M Martensson-Pendrill *et al*., J. Phys. B: At. Mol.opt.Phys. 23(1990)

Energy levels:

- ^{43}K: Measday *et al*., PRC 73, 045501 (2006)
- ^{45}K: Huck *et al*., PRC 21, 2 (1980)
- ^{47}K: Weissman *et al*., PRC 70, 024304 (2004)
- ^{49}K: Broda *et al*., PRC 82, 034319 (2010)
- ^{51}K: Perrot *et al.,* PRC 74,014313 (2006)

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